POLLUTION OF SUBSURFACE WATER BY SANITARY LANDFILLS

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This study was to provide quantitative information as to the behavior of sanitary landfills under natural and simulated environmental conditions in an environment common to southeastern Pennsylvania and a large portion of the region extending between Washington, D.C., and Boston, Massachusetts. The long-range objectives were: (1) To provide means for predicting the movement of pollutants in subsurface regions under existing and proposed sanitary landfill sites. (2) To develop hydrologic, geologic, and soil criteria for the evaluation of site suitability for sanitary landfill operations. (3) To appraise design methods and remedial procedures for reducing any undesirable contaminant movement. A laboratory and a field sanitary landfill were developed to generate the data needed to attain these long-range objectives. This report consists of three volumes: this volume (available from the U.S. Environmental Protection Agency, Cincinnati, Ohio 45213) describes the experimental facilities; Volume 2 (available from the National Technical Information Service, Springfield, Virginia 22151) contains the experimental data collected from Oct. 1, 1967, to Dec. 31, 1968; Volume 3 (also available from the National Technical Information Service) contains the experimental data collected from Jan. 1, 1969, to Sept. 29, 1969.

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FOREWORD

An important objective of the Office of Solid Waste Management Programs is to aid in developing economic and efficient solid waste management practices. As authorized under the Solid Waste Disposal Act (Public Law 89-272) and the Resource Recovery Act (Public Law 91-512), the Office has awarded almost 100 research grants to nonprofit institutions in this effort to stimulate and accelerate the development of new or improved ways for handling the Nation's discarded solids.

The present document reports on work done under one of these research grants. Received from the grantee in three volumes, only the first volume, a narrative description of the project, is reported herein. Volumes 2 and 3, which are compilations of the experimental data collected, will be available through the National Technical Information Service, Springfield, Virginia 22151.

Research Grant EP-000162 has been renewed to cover an additional 3 years of research. Volume 4 of this series is an interim report covering an additional year of testing and evaluation. This volume is currently being processed and will be published in early 1972. A final report covering the entire 6-year project period is expected for publication in the fall of 1972.

It is recognized that a sanitary landfill, unless properly engineered and on a suitable site, can pollute subsurface water. To determine the kind and degree of contamination under varying field and laboratory conditions was an aim of this project. From this, criteria were developed which can be useful to others in the design of landfills and prediction of their performance.

ACKNOWLEDGMENT

Those who have been associated with this study are acknowledged, particularly the participation of Irwin Remson, A. W. Lawrence, and Norman Trieff. The cooperation of the participants from the Pennsylvania Department of Health, especially Grover Emrich, is also acknowledged.

The field site location was provided by the Southeastern Chester County Landfill Authority, A. Nixon, Director. Their cooperative spirit throughout this study is sincerely appreciated.

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INTRODUCTION

In an attempt to minimize health and pollution hazards, due to the disposal of solid waste by landfilling, sanitary landfill design criteria have evolved which are primarily empirical in nature and which may or may not have a relationship to environmental conditions (1, 2). Several studies of sanitary landfill behavior have been undertaken in recent years to better understand them and to delineate and define significant design criteria (3-9). Unfortunately, many of the results obtained from these studies, most of which were limited in scope, reflect only local conditions and cannot be easily extrapolated outside the specific region.

The study described in this report was undertaken by Drexel University in cooperation with the Pennsylvania Department of Health. Interest on the part of the Pennsylvania Department of Health was stimulated by its concern with the decreasing availability of suitable landfill sites within the state and the increasing frequency of pollution and health problems resulting from solid waste disposal.

The study, as conceived, was to provide quantitative information as to the behavior of sanitary landfills in an environment common to southeastern Pennsylvania, and in fact, to a large portion of the region extending between Washington, D. C. and Boston, Massachusetts. To suppress local environmental influences, the study was developed so as to generalize results, except those specifically related to the southeastern Pennsylvania region.

The long range objectives were:

To provide means for predicting the movement of pollutants in subsurface regions under existing and proposed sanitary landfill sites,

To develop hydrologic, geologic and soil criteria for the evaluation of site suitability for sanitary landfill operations, and

To appraise design methods and remedial procedures for reducing any undesirable contaminant movement.

The study was developed as an integrated experimental-theoretical analysis of the behavior of domestic sanitary landfills. As such, it was necessary to carry out both aspects of the investigation simultaneously. Attainment of all project objectives, during the initial study period, was not envisioned, and the type and anticipated duration of the experimental studies required that maximum initial emphasis be placed on their development.

The majority of this report is a description of the experimental facilities, a discussion of the experimental data obtained during the study, and a discussion of that data. The remainder of the report is concerned with a model for predicting the quantity and time variation of leachate. The significant parameters, which control leachate generation, are discussed.

SUMMARY AND CONCLUSIONS

Attainment of project objectives required the evaluation of a substantial amount of quantitative data for a sanitary landfill in a temperate-humid climate; however, available information at the time of project initiation was not adequate. Two experimental facilities, a laboratory sanitary landfill and a field sanitary landfill, were developed. The laboratory facility was operated under controlled environmental conditions, while the field facility was operated under natural (no control) environmental conditions.

The laboratory sanitary landfill facility was the first placed into operation, and as a result, it generated the maximum amount of experimental data. A major portion of this report is devoted to a discussion of this facility and related experimental data. The field sanitary landfill was made operational approximately six months after the initiation of the laboratory study. A description of this facility and the experimental data which was available at the time of report preparation is presented.

The laboratory sanitary landfill was contained in a lysimeter, which consisted of a fiberglass-lined steel tank, thirteen feet high and six feet by six feet in cross-section. A bottom collection trough was used to collect the landfill-generated leachate. The top of the lysimeter was closed and temperatures and water input were adjusted on a pre-determined schedule. The lysimeter vertical sidewalls were insulated to minimize heat exchange with the laboratory proper, while the bottom of the lysimeter was controlled at a constant temperature. Essentially, the lysimeter functioned as a closed system which permitted the contained landfill to be representative of the center of a large sanitary landfill, the depth of which was small in comparison to its areal extent.

Lysimeter leachate and gas samples were analyzed, and temperatures were monitored on a routine basis. While information on gases and temperatures was not essential to attainment of project objectives, the collection was necessary in order to obtain a complete picture of the behavior of sanitary landfills.

The field facility consisted of a 50 foot by 50 foot site with eight feet of refuse and a two-foot soil cover. Temperatures, gases and leachate quality within the landfill, as well as temperatures, gases and leachate quality outside the landfill, were collected on a routine basis. Also monitored were precipitation and ground water quality, both under and away from the landfill site.

The laboratory landfill behavior pattern is representative of a young low-compaction density refuse. Within ten days of its initiation, refuse temperatures reached 150°F at the refuse center. Temperatures at adjacent levels were lower, however, with time there was a general spreading of temperatures from the refuse center to the top and bottom temperature-controlled boundaries. Temperatures at levels other than the center did not exceed 134°F. The temperature pattern is probably unique to the particular system; that is, a young low-density rapidly placed landfill; however, the pattern is representative of a refuse which undergoes initial high aerobic activity; it is probable that with other placement conditions, temperature peaks would occur at different refuse levels, at different times and at different maximums. Maximums greatly in excess of the 150°F range experienced in this study should not be expected.

Lysimeter temperatures stabilized at approximately 80°F, approximately 60 days after refuse placement. The general temperature pattern obtained indicated that the refuse was initially in a general aerobic state, and that after 60 days, an anaerobic condition became dominant.

After the refuse temperatures became virtually steady state, that is when the refuse became anaerobic, changes in top boundary temperatures had little influence on internal temperature levels or distribution. The behavior implies that alteration of internal temperatures, due to changes in environmental temperatures, are minimized by soil and refuse insulating properties, as well as by changes in biological activity. The net result of all temperature influences is a virtually constant internal temperature state.

The lysimeter temperature and gas behavior patterns indicated the simultaneous existence of aerobic and anaerobic regions in a refuse. During its early life, aerobic conditions dominated, while during its later life, anaerobic conditions dominated. The percentages and distribution of aerobic and anaerobic states in each region varied with time, because any flushing of the landfill by water infiltration introduced fresh air.

The lysimeter began to produce leachate almost immediately, even though the refuse was placed at a very low moisture content. The quantities of leachate produced were small; nevertheless, the pollution levels, as measured by chemical parameters, were extremely high. The low quantity of initial leachate production is due to the low initial moisture content of the lysimeter components and most of the initial water introduced into the lysimeter functioned to bring each system component to field capacity. At field capacity, net infiltration and leachate quantities were approximately equal.

Results of the leachate quantity studies indicate the phase relationship between water input and leachate production. During periods of low leachate production, any additional decrease further reduced or eliminated leachate production. Conversely, as water input increased, leachate production also increased. The phase relationship existed even when the system was not at field capacity. Leachate production can be attributed to one or all of the following sources:

1. the refuse
2. channeling
3. an advanced wetting front
4. the main wetting front.

From the results of this study, it is concluded that sources 1 and 2 would be responsible for leachate collected from a landfill during the early time period when the landfill had been placed at a relatively low initial moisture content. Once the system reached field capacity, leachate contributed by these sources would be primarily due to source 3. Finally, when the system reached field capacity, leachate production would be due to movement of the main wetting front, source 4.

A landfill system whose components were placed at field capacity would produce leachate immediately, and the source would be primarily the main wetting front. One effect of these various leachate generation patterns is to alter the leachate composition. Leachate produced during the slow attainment of the system field capacity will probably exhibit initial pollutant concentrations different than a landfill in which substantial quantities of leachate are produced immediately. Once the system transients have been eliminated, both landfills should produce similar, but not necessarily identical, leachates.

The results of the significant parameters monitored in the lysimeter are summarized as follows:

1. pH - generally, solutions were acidic with a mean pH of 5.5. It is believed that flow rate through the refuse is a major controlling factor in establishing leachate pH and that with maximum flow rates, pH will be acidic. The general acidic nature of the leachate compounds the potential pollution problem because low pH values tend to reduce exchange capacities of renovating soils at the time when quantities are high.

2. Iron - iron concentrations tended to be higher when leachate production was high, reaching their maximums at times of maximum leachate production. Leachate iron concentrations were in excess of 1600 mg/l during high quantity periods.

3. Zinc - zinc concentrations were as high as 120 to 135 mg/l. More usual concentrations levels were between 15 and 30 mg/l. Significant quantities of zinc did not appear in the leachate until about 430 days into the test. However, after its first appearance, its presencewas continuous. This pattern suggests the delayed release of zinc ions due to the breakdown of some refuse component which had previously resisted leaching action.

4. Phosphate - high phosphate concentrations occurred shortly after initiation of the test. At that time they reached concentration levels of approximately 130 mg/l. After the initial peak, levels were much lower, never exceeding 30 mg/l. There also were long spans of time when no detectable phosphate concentrations were present.

5. Sulfate - sulfates were present during the entire period of the test. Concentrations generally increased as time elapsed. Toward the

end of the test period, sulfate concentrations peaked between 400 and 500 mg/l. In general, sulfate concentration levels increased with increased leachate production, and as the system approached field capacity.

6. Chloride - chloride was present during the entire test period. Concentrations were approximately 200 to 300 mg/l. Localized peaks occurred soon after initiation of the test where a peak of 700 mg/l was attained and approximately one year into the test when approximately 2400 mg/l were attained.

7. Sodium - sodium was present during the entire test period. While sodium concentrations reached 3800 mg/l between 200 and 250 days into the test, this peak was not sustained and was much greater than the usual values. More frequent concentration levels were in the 200 to 300 mg/l range. Toward the end of the test period, concentration levels tended to increase.

8. Nitrogen - ignoring an initial peak of 482 mg/l, initial nitrogen levels were approximately 8 mg/l. After initiation of the test, there was a general increase in nitrogen levels to between 100 and 200 mg/l. At the time of project termination, nitrogen levels had reached as high as 200 mg/l and showed an increasing trend.

9. Hardness (as $CaCO_3$) - the most frequently recorded hardness values ranged between 2250 and 2750 mg/l. A local peak of approximately 5500 mg/l occurred about 450 days into the test.

10. COD - the most frequent concentration levels for COD were between 20,000 and 22,000 mg/l. An initial localized peak of 50,000 mg/l was recorded within one month of the initiation of the test. It is believed that this initial peak was caused by the release of some organic components due to compaction and placement of the refuse.

11. Suspended Solids - Initial concentrations ranged from 1000 to 2000 mg/l but quickly dropped to average approximately 200 mg/l for the first 400 days of the test. At that time, they increased with increasing volumes of leachate, to average 750 mg/l.

12. Total Solids - total solids ranged between 10,000 and 28,000 mg/l with an initial peak of 40,000 mg/l.

13. Nickel - no nickel was detected in the leachate until 150 days into the test; after that time, concentration levels did not exceed 0.9 mg/l. Most frequently concentration levels fell between 0.2 and 0.3 mg/l. Like zinc, once nickel was detected in the leachate, it was present on a continuous basis. This again indicates the initiation of some release mechanism which was not active prior to that time.

14. Copper - copper concentrations were erratic. In general, copper concentrations were less than 0.1 mg/l although peaks occurred between 100 and 200 days into the test at a level of approximately 5 mg/l, and again a peak at approximately 600 days into the test occurred at a level of about 7 mg/l.

Gas samples taken from various depths within the refuse were analyzed on a routine basis for carbon monoxide, hydrogen sulfide, nitrogen, oxygen carbon dioxide and total hydrocarbons reported as methane. No carbon monoxide or hydrogen sulfide were detected. Oxygen, carbon dioxide, methane and nitrogen were found to exist in refuse void gases. In general, the percentage of oxygen decreased with depth and increasing time, and the percentage of carbon dioxide and methane increased with depth and increasing time.

While the hydrocarbon gas is reported as methane, the accumulation of increasing percentages with depth indicate that it is possibly a denser, higher molecular weight gas than methane. The lack of significant methane in the top port indicates little migration of the gas occurred. The gas results were a clear indicator of the point of transition from aerobic to anaerobic conditions. As an indicator of the degree of activity, it is believed that gas constituents are more indicative of the landfill age than temperatures.

While the field facility experimental data was incomplete at the time of this report, there are some data which is worthy of consideration. Temperatures at the various levels indicated that the high level of biological activity within the lysimeter refuse did not occur within the field refuse. There are two reasons for this; first, due to ease of compaction, higher field refuse densities were attained, and secondly, field temperatures during the refuse placement were lower on an average daily basis than those in the laboratory. These two conditions, higher density and lower temperatures, combined to moderate the initial biological activity. The overall temperature behavior of the landfill is similar to that of the laboratory lysimeter. Internal temperatures tend to moderate and not be influenced by environmental conditions once a substantial period has elapsed after test initiation.

The gas data for the field landfill indicates that a high percentage of carbon dioxide was present from the start of the test. Oxygen and methane levels were relatively low. Because the field landfill was not under very stable conditions, curves were erratic and no definite conclusions could be reached about the landfill characteristics.

The character of the ground water which underlies the landfill was recorded. In general, the ground water quality met drinking water standards. Between the time of the initiation of the field landfill and the preparation of this report, no significant contamination was detected within the ground water wells.

A portion of the project was concerned with a moisture routing model for predicting the leachate production pattern of a sanitary landfill. The model was developed for a one-dimensional, downward vertical flow system and was based upon the equation of continuity. Water input was due only to surface infiltration.

Use of the model requires knowledge of the hydraulic characteristics of the cover soil and refuse. A computer program for model utilization is presented in Appendix 5.

The model was used to study the experimental laboratory and field sanitary landfills used in this project, as well as several hypothetical landfills. The study of the laboratory sanitary landfill provided a test of model reliability. It was concluded that the model is reasonably valid; differences between computed and actual times are attributed to:

1. The fact that the experimental landfill did not behave exactly like the theoretical field capacity model; that is, no downward movement of moisture until field capacity is attained in a particular layer.

2. The refuse field capacity probably changes during its life cycle, and,
3. The refuse field capacity and its initial moisture content data are only reasonable approximations of actual values.

The results of the study of several hypothetical sanitary landfill sites across the country indicate that landfills in over half the nation will produce leachate if there is a net water infiltration. First appearance of leachate is dependent on site conditions, including surface grading, vegetation and soil parameters. The parameters include type, thickness, density, permeability, field capacity and initial moisture content. Refuse parameters which control leachate appearance include type, thickness, original moisture content, field capacity and initial density. Based on field and laboratory studies of ground and underground refuse, it was shown that grinding significantly increased field capacity as refuse size decreased; however, for a given ground size the field capacity tended to approach an asymptote which is unique for that size.

It is concluded that most landfills will eventually produce leachate, as well as gases. Whether or not the leachate is visible depends on the landfill's discharge pattern. If the site development encourages leaching to surface areas, then its appearance will be obvious; on the other hand, when leaching occurs directly to ground water bodies, its effect can only be detected by monitoring wells which must be carefully installed and developed.

The leachate produced by a sanitary landfill developed with current refuse composition during its early life is highly polluted. The leachate is acidic (pH of 5.5) and carries many dissolved and suspended solids which place a burden, both as to quantity and quality, on the capability of underlying soils to provide renovation prior to contact with the ground water system.

EXPERIMENTAL FACILITIES

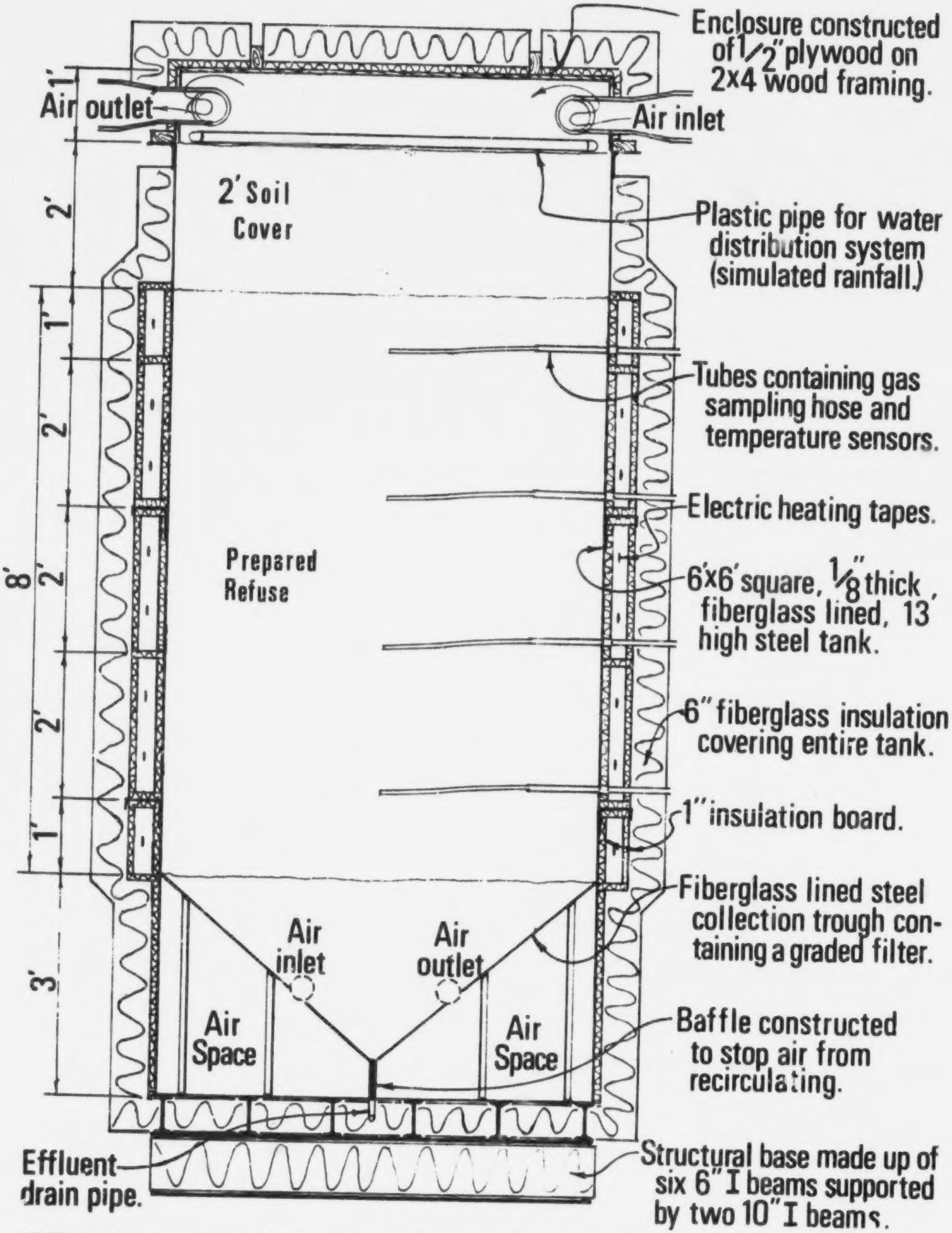
The experimental facilities provided the data necessary to develop a complete picture of the behavior of a sanitary landfill (as currently defined) under natural and simulated environmental conditions. The laboratory lysimeter functioned as a leachate and gas generator under controlled environmental conditions, while the data from the field facility were obtained under natural environmental conditions.

LABORATORY SANITARY LANDFILL LYSIMETER

Several designs for the laboratory lysimeter were evaluated during the initial stages of the project. The final design, which is presented herein, represents the results of that effort. The lysimeter simulated the center of a sanitary landfill with an 8-foot-thick (at time of placement) refuse layer covered with a 2-foot soil layer. These dimensions were chosen since they were representative of current practice (1, 2), and it was believed that by using these values, an initial quantitative understanding of the behavior of many existing landfills would result. A major design criteria was that the lysimeter environmental conditions should represent climate conditions common to southeastern Pennsylvania for a landfill located above micaceous granite gneiss bedrock in soils derived therefrom. All design criteria were based on a requirement that the laboratory landfill data could be correlated with the field facility data.

Design Criteria

In order to simulate an in-situ sanitary landfill, several site and


Enclosure constructed of 1/2" plywood on 2x4 wood framing.
Air outlet
Air inlet
1'
2'
2' Soil Cover
Plastic pipe for water distribution system (simulated rainfall.)
1'
Tubes containing gas sampling hose and temperature sensors.
2'
Electric heating tapes.
8'
2'
Prepared Refuse
6'x6' square, 1/8" thick, fiberglass lined, 13' high steel tank.
2'
6" fiberglass insulation covering entire tank.
1'
1" insulation board.
Fiberglass lined steel collection trough containing a graded filter.
3'
Air inlet
Air outlet
Air Space
Air Space
Baffle constructed to stop air from recirculating.
Effluent drain pipe.
Structural base made up of six 6" I beams supported by two 10" I beams.

LYSIMETER CROSS SECTION—SIMULATED SANITARY LANDFILL

FIG. 1

on the laboratory floor.

Leachate collection was facilitated by using an inverted pyramid-shaped trough (Fig. 2) which was located in the bottom of the tank and was constructed of low carbon steel covered with fiberglass. The side slopes of the trough were 1 on 1, and positioned at its apex was a 1/4-inch stainless steel pipe for leachate removal The interior of the trough was filled with Ottawa sand and glass beads sized and arranged as shown in Figure 3. The sizes of the sand and beads were selected to permit free passage of leachate. The total height of the trough was three feet, which reduced the effective interior tank height to ten feet.

Environmental System

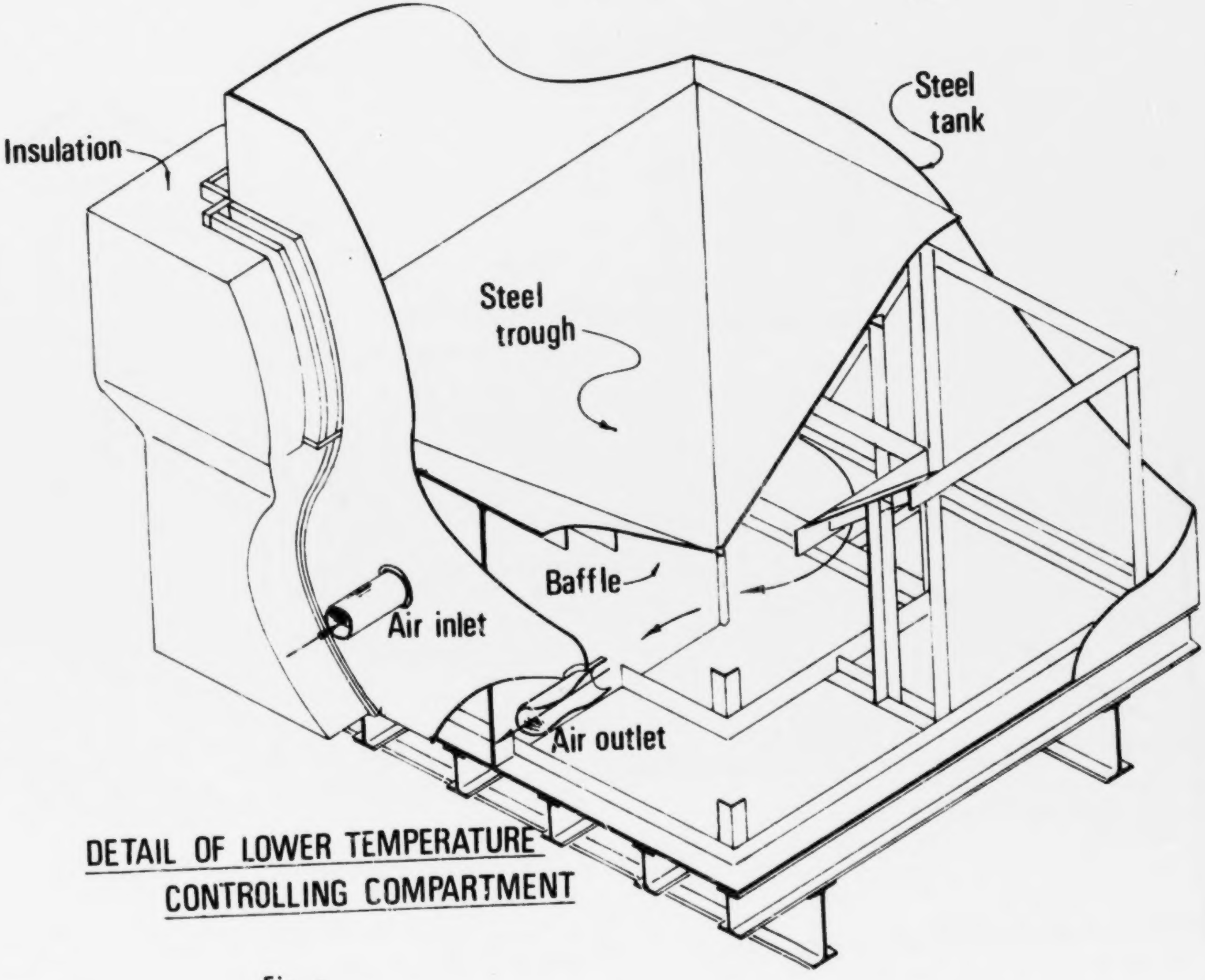
Bottom Air Temperature Control

The air space beneath the trough was maintained at a temperature of 57.2°F. This temperature was equivalent to the average yearly soil temperature at a depth of ten feet below the ground surface in southeastern Pennsylvania. A schematic of the cooling system is shown in Figure 4, section B-B. A section through the air space is shown in Figure 1.

Top Air Temperature Control

Air temperature above the landfill was changed monthly to conform with the average monthly air temperatures in southeastern Pennsylvania. The average monthly air temperatures are listed in Table 1. Two systems were used to control this temperature.

The first system consisted of a controlled temperature air sweep which passed directly over the free surface of the cover soil. This system is shown in schematic in Figure 4, section A-A in the cross-section



DETAIL OF LOWER TEMPERATURE CONTROLLING COMPARTMENT

Fig. 2

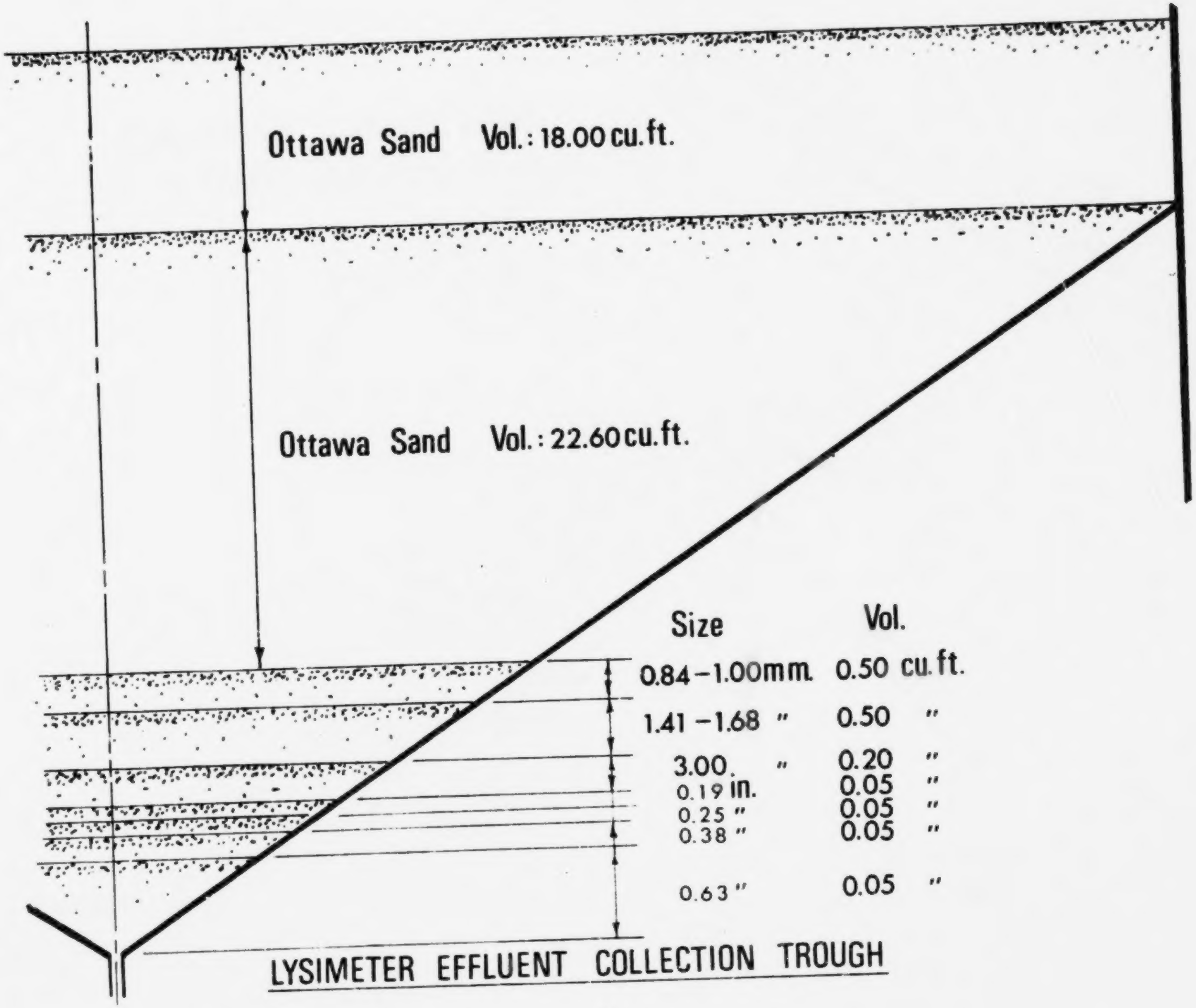
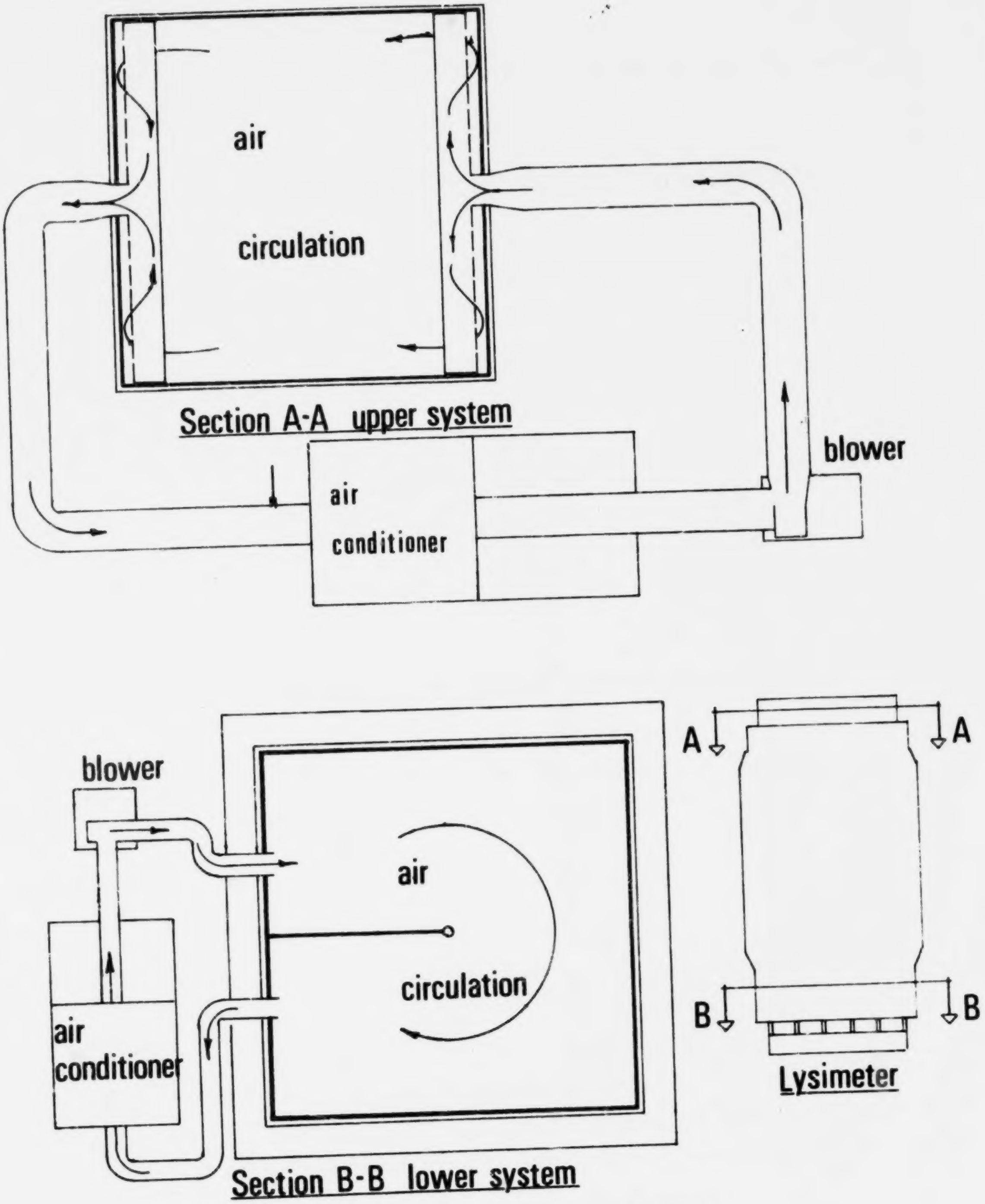

Ottawa Sand Vol.: 18.00 cu.ft.
Ottawa Sand Vol.: 22.60 cu.ft.
Size
Vol.
0.84-1.00mm. 0.50 cu.ft.
1.41-1.68 " 0.50 "
3.00. " 0.20 "
0.19 in. 0.05 "
0.25 " 0.05 "
0.38 " 0.05 "
0.63 " 0.05 "
LYSIMETER EFFLUENT COLLECTION TROUGH

Fig 3



DETAILS OF AIR CIRCULATION SYSTEM

Fig. 4

TABLE 1

Environmental Data for Southeastern Pennsylvania

Average Monthly Air Temperatures

Month	Temperature °F
January	33.4
February	33.8
March	41.3
April	52.1
May	62.7
June	71.4
July	76.0
August	74.3
September	67.6
October	56.6
November	45.1
December	35.1

Average Monthly Water Available for Infiltration

Month	P-ET (inches)*	Gal./month**
January	3.40	76,306
February	2.95	66,207
March	3.40	76,306
April	1.66	37,255
May	.18	4,040
June	-1.18	0
July	-1.85	0
August	.28	6,284
September	.21	4,713
October	.89	19,974
November	2.78	62,392
December	3.03	68,002

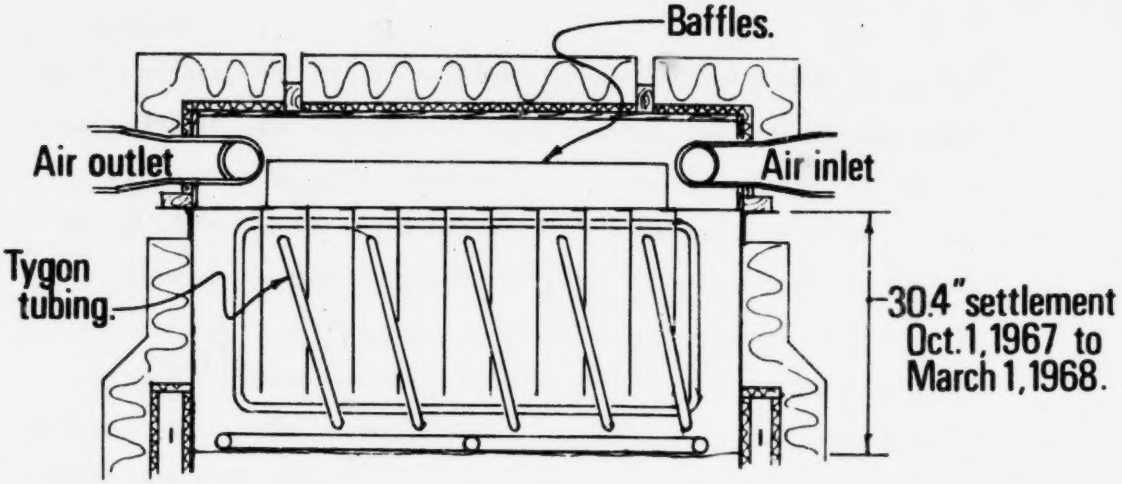
*Precipitation minus Evapotranspiration.

**Gallons per month on a 36-square-foot area. Water is added weekly.

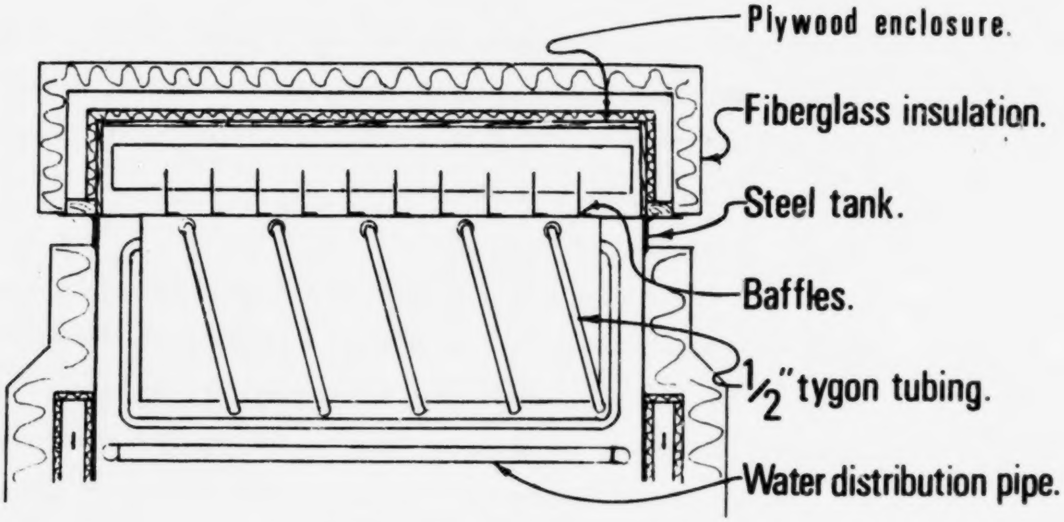
through the tank (Fig. 1). Early in the operation of the lysimeter, it was found that the air sweep across the soil introduced a small (a difference of less than one inch of water) positive pressure in the voids of the refuse. While the presence of this pressure presented no serious system function problem, it was believed that it might affect gas movement within and out of the refuse. To eliminate the problem of positive air pressure, a system using cooling water circulating through 300 feet of 1/2-inch Tygon tubing was developed. This system is shown in cross-section in Figure 5 and in schematic in Figure 6. Cooling water was pumped through the tubing at the rate of 1 1/2 gallons per minute and its temperature was controlled by an immersible cooling coil placed in a 55-gallon tank. It was possible to place this system directly on the top of the free soil surface due to refuse settlement (see section on compaction). This system and the original air system which was separated from the soil surface by a sealed steel plate interacted effectively in maintaining air temperatures above the soil surface.

Water Application System

Distilled water was added to the top of the soil cover, when needed, on a weekly basis. The water added represented the excess of precipitation over evapotranspiration for southeastern Pennsylvania. The The quantities applied are given in Table 1. The water was distributed over the soil surface by means of 1 1/4-inch rigid plastic pipe with 1/16-inch diameter holes drilled in the top. The pipe system was gravity fed from outside the tank under a head of three feet. Using this system, the water "rained" lightly on the soil surface.



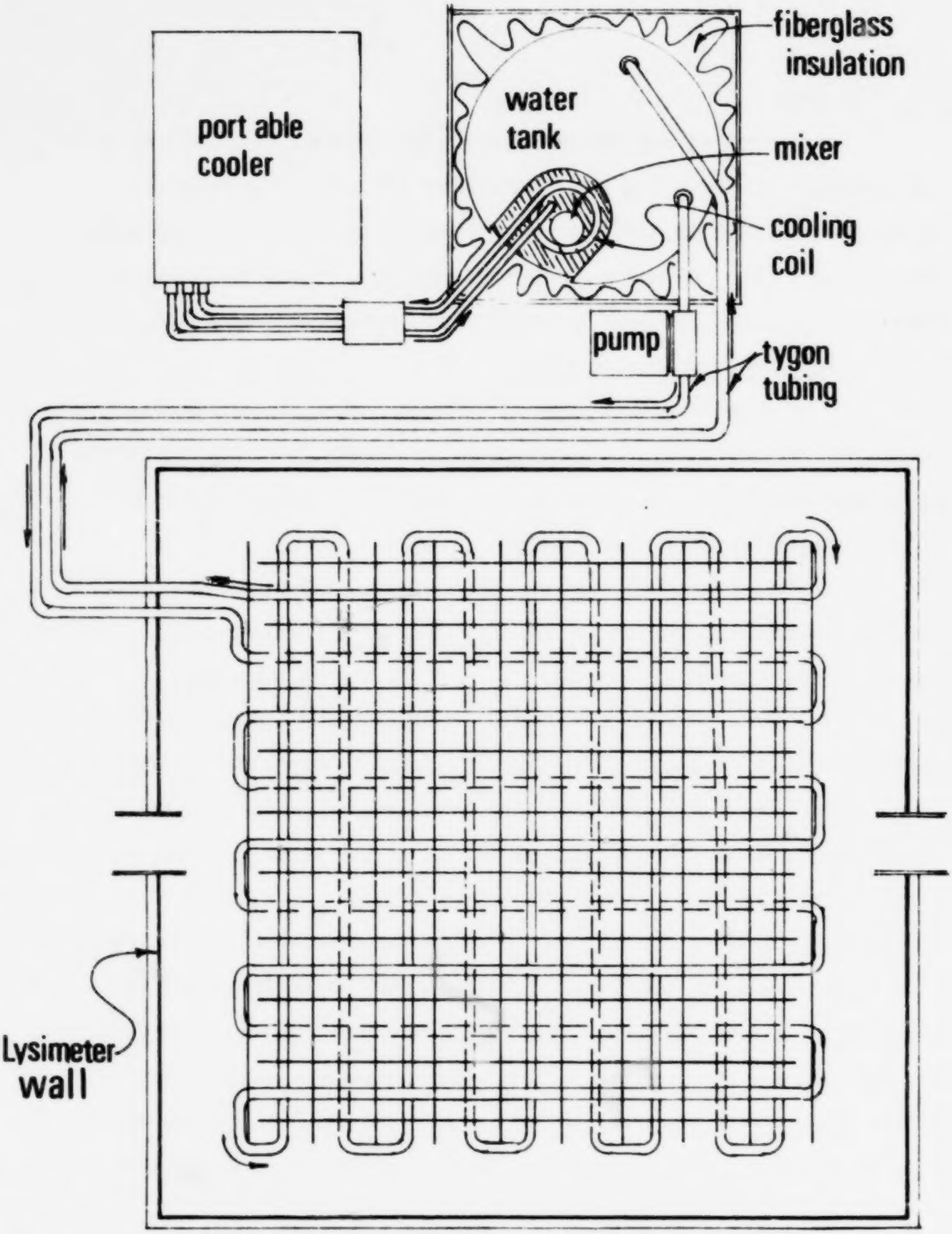
FRONT



SIDE

LYSIMETER COOLING SYSTEM (MODIFIED)
to simulate environmental temperature.

Fig 5



SCHEMATIC - WATER COOLING SYSTEM

Fig 6

Insulation

Minimizing of heat exchange through the lysimeter's vertical walls was most essential to its use as a simulator of the center of a landfill. To control heat exchange, the vertical walls of the lysimeter were completely insulated (Fig. 1). Two inches of urethane insulation board, six inches of fiberglass insulation, stagnant air pockets and heating tapes were used.

Heat Flow into the Lysimeter

Movement of heat into the lysimeter, when internal temperatures were less than laboratory temperatures, was minimized by the combination of urethane insulation board, fiberglass insulation and stagnant air pockets.

Heat Flow out of the Lysimeter

Flow of heat out of the lysimeter was controlled by the same insulation system mentioned in the previous section, and heating tapes located in the stagnant air pockets (Fig. 1). The heating tapes were energized by thermistor-activated controllers which supplied power. These bands of "active" insulation covered one-foot segments at the top and bottom of the refuse zone and three two-foot intermediate zones. Each zone had its own controller and functioned independently of the others. The use of zoning permitted control of heat outflow at each level. Local control was necessary when temperatures inside the lysimeter were not constant vertically.

When the laboratory temperatures were higher than the interior temperatures, at any level, the tapes did not heat the stagnant air pockets. However, when the temperature at a particular level in the lysimeter was greater than the laboratory temperatures by at least 1°F, the corresponding tape was turned on by the controller. Power to heat the tapes was supplied in an amount proportional to the temperature difference, but at a rate so as to minimize overshooting of the desired temperature. The tapes were turned on until the difference between the internal temperature, at any level, and the corresponding stagnant air space temperature was less than 1^{0}F. When a difference of 1^{0}F or less was reached, the tapes were inactivated.

In addition to the controlling thermistors, an auxiliary set of thermistors were used to monitor the behavior of the heating tapes. Location of a typical set of thermistors and a schematic of the controller are shown in Figure 7.

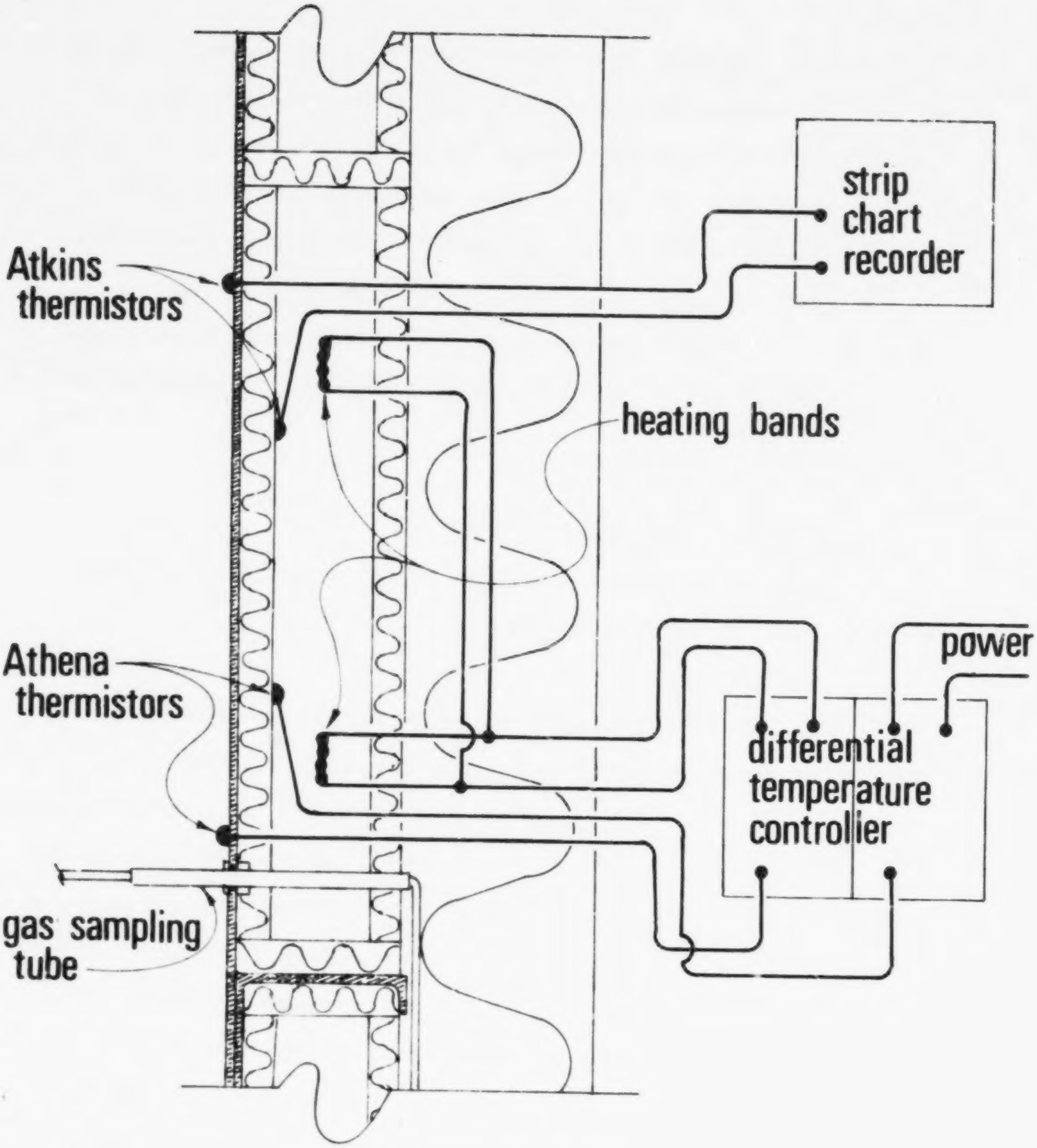
Instrumentation and Sampling

Three major parameters were monitored: temperatures, gases and quantity and composition of the leachate.

Temperatures

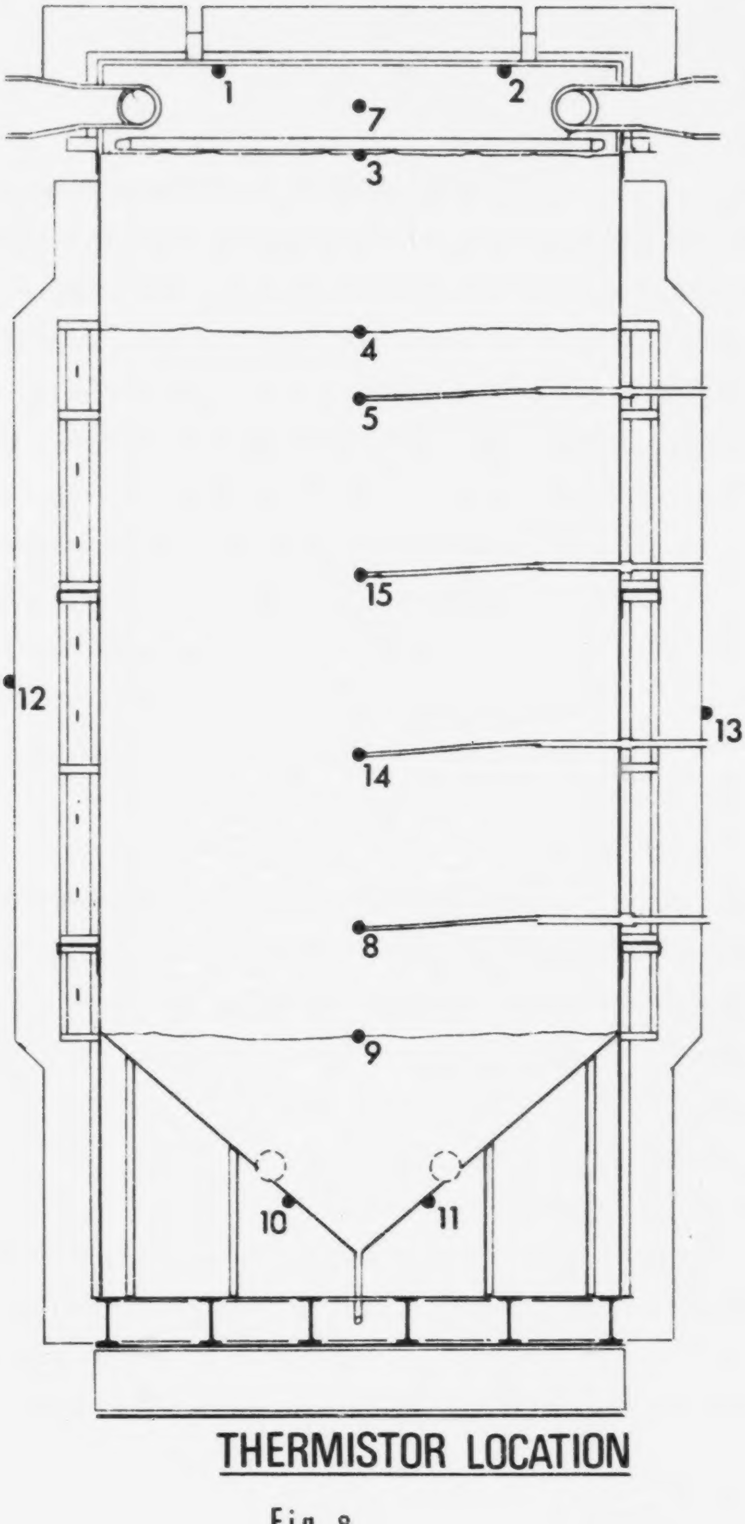
An automatic scanning-printing system using thermistors and a digital thermometer was used to monitor temperatures. Temperatures were measured at seven locations inside the lysimeter and at two exterior locations. Thermistor locations, at time of fill placement, are shown in Figure 8. The thermistors monitored temperatures in the air space above the soil cover, at the air-soil cover interface, at the soil cover-refuse interface, at 1, 3, 5 and 7 feet below the top of the refuse, at the refuse-Ottawa sand interface, in the bottom air sweep and at two locations outside the tank.

Initially, temperatures were recorded every hour, but the system was changed over to a four-hour record time after the temperature changes ceased being highly transient.



HEATING CONTROL SYSTEM

Fig 7



THERMISTOR LOCATION

Fig 8

TABLE 2

List of Liquid and Gas Sample Analyses

Liquid

pH
Hardness
Dissolved oxygen
Phosphate
Chloride
Sodium
Suspended solids
Total residue (total dissolved solids)
Nitrogen (ammonia, organic)
Nitrate
Chemical oxygen demand
Biological oxygen demand
Iron
Zinc
Copper
Nickel
Sulfate

Gas

Carbon dioxide
Oxygen
Nitrogen
Methane (Total Hydrocarbons)
Hydrogen sulfide
Carbon monoxide

TABLE 3

Refuse Composition
Laboratory Lysimeter

Percent Composition of Refuse [10]

Percent	
23.38	Corrugated paper boxes
9.40	Newspapers
6.80	Magazine paper
5.57	Brown paper
2.75	Mail
2.06	Paper food cartons
1.98	Tissue paper
0.76	Plastic coated paper
0.76	Wax cartons
2.29	Vegetable food wastes
1.53	Citrus rinds and seeds
2.29	Meat scraps, cooked
2.29	Fried fats
2.29	Wood
2.29	Ripe tree leaves
1.53	Flower garden plants
1.53	Lawn grass, green
1.53	Evergreens
0.76	Plastics
0.76	Rags
0.38	Leather goods
0.38	Rubber composition
0.76	Paints and oils
0.76	Vacuum cleaner catch
1.53	Dirt
6.86	Metals
7.73	Glass, ceramics, ash
9.05	Adjusted moisture
100.00	

Component	Gms. Pollutant/gm. dry refuse or wt.percent
Crude fiber	38.3%
Moisture content	18.2%
Ash	20.2%
Free carbon	0.57%
Nitrogen	
a) free	.02 mg/gram
b) organic	1.23 "
Water solubles:	
a) sodium	2.33 "
b) chloride	.97 "
c) sulfate	2.19 "
C.O.D.	42.49 "
Phosphate	.15 "
Hardness	10.12 mg/$CaCO_3$/gm.
Major Metals:	
Aluminum, Iron, Silicon	>5.00%(By spectrographic analysis)**
Minor Metals:	
Calcium, Magnesium, Potassium	1.0-5.0% (By spectrographic analysis)**

**Of non-volatile portion.

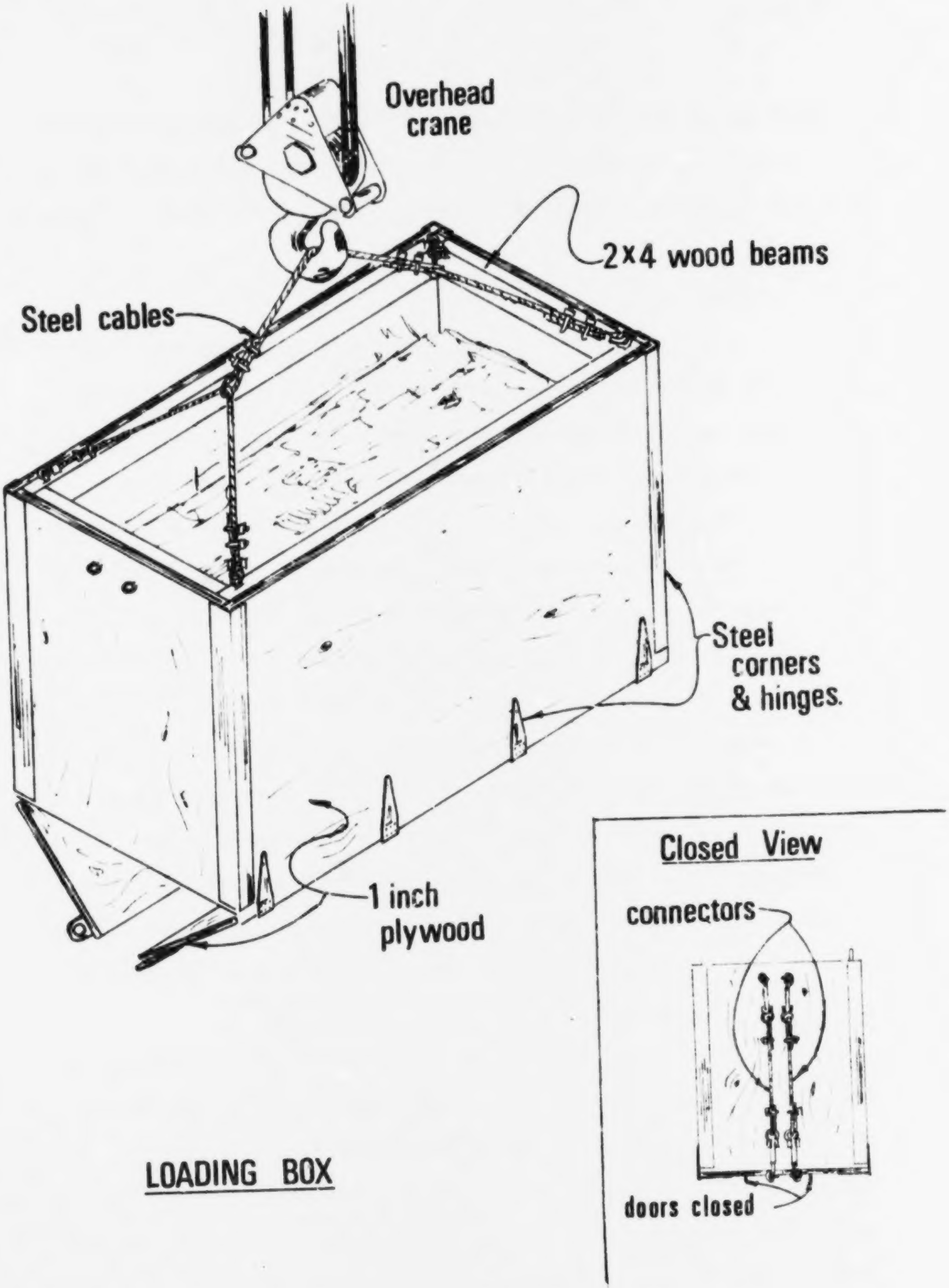
and unrolled cans were used to eliminate compaction and placement problems due to arching and large voids. Other paper products, glass, plastics, etc. were also sized to prevent their having an unrealistic influence on lysimeter functioning.

Compaction

A procedure was developed for external compaction, since it was not possible to compact the refuse within the lysimeter. The general scheme consisted of filling (with a mixture of prepared refuse) six foot by three foot by two foot wooden boxes which had a trap door bottom (Fig. 9). The refuse components were premixed by hand prior to placement. The refuse was then compressed in the box in the steel frame, shown in Figure 10, by using a steel coverplate loaded by the hydraulic jack. The frame was designed to facilitate insertion and removal of the refuse boxes.

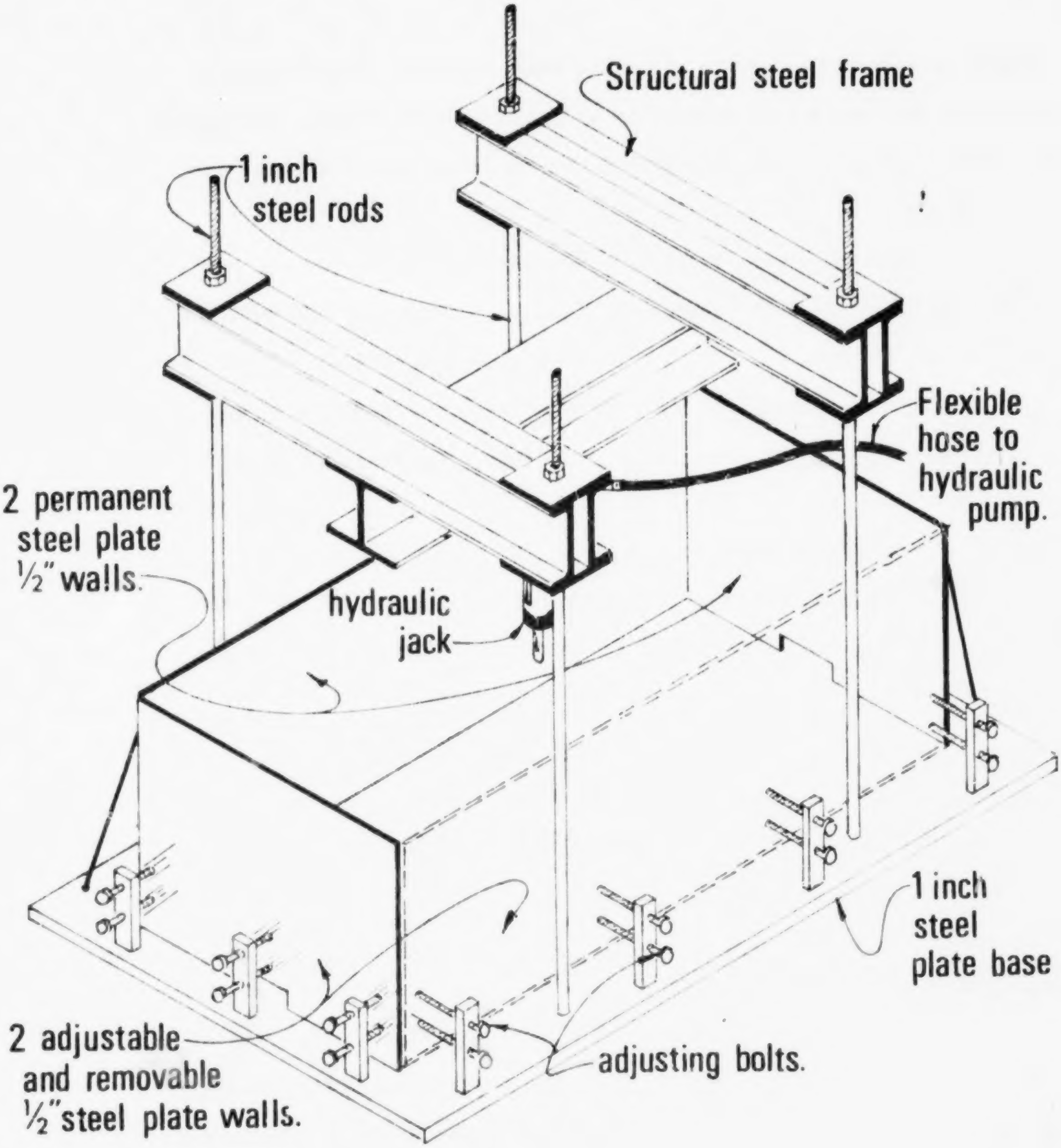
The refuse was compacted until the original height of two feet had decreased to one foot for a compaction ratio of 2:1. The 2:1 compaction ratio occurred when the unit pressure on the refuse was approximately six pounds per square inch. As discussed elsewhere (11), use of the 2:1 compaction ratio criteria did not prove entirely satisfactory. Upon release of the compaction pressure, a rebound of approximately two inches occurred. At the compaction ratio of 2:1, a dry density at placement of approximately 327 lbs/yd^3 was obtained.

After compaction in the frame, each load was placed in the tank by means of an overhead crane. Eight one-foot layers of compacted material were required to fill the tank to the desired refuse height. Each layer required two loads for a total of sixteen compactions. To place the refuse, the loading box was first positioned so that the bottom trap door rested on previously placed material. Then, the end straps (Fig. 10) were



LOADING BOX

Fig 9


Structural steel frame
1 inch steel rods
Flexible hose to hydraulic pump.
2 permanent steel plate ½" walls.
hydraulic jack
1 inch steel plate base
2 adjustable and removable ½"steel plate walls.
adjusting bolts.

REFUSE COMPACTION FRAME

Fig 10

removed and the box raised to allow the doors to open. This procedure permitted the compaction material to be deposited with minimum disturbance. All voids, corners, etc., were hand filled to insure elimination of any large channels.

After placement, the refuse was covered with two feet of soil taken from the field site (described in the next section). The soil was hand tamped into position, and at placement, had a density of 110 lbs/ft^3.

The total weight of the soil cover resulted in approximately 1 1/2 lbs/in^2 of contact pressure on the refuse. The immediate settlement produced a refuse dry density of 378 lbs/yd^3. This refuse surface settlement was approximately equal to the sum of the individual rebounds (16 inches) that occurred after each compaction. It was less than the total of the rebounds since during the loading of the tank, each refuse layer caused some recompression of underlying layers.

Photographs

Photographs of the lysimeter and its installation are given in Appendix 2.

FIELD SANITARY LANDFILL FACILITY

During the planning stages of this study, several existing landfills were evaluated for their potential use. The primary reason for acceptance of the site utilized was the fact that it was a new landfill, which could be studied from time of initial placement. Other factors which were weighed in the final determination were the quality of the proposed landfilling operation, the natural terrain of the site, the proximity to Drexel, and the site location relative to existing human habitation. Specific reasons for selection of this site, relative to ground water and site geology, are enumerated in the section on location.

Location

The test site was a portion of the southeastern Chester County Sanitary Landfill located in Kennett Township, Chester County, Pennsylvania at the intersection of North Walnut Street and Route #1 Bypass (Fig. 11). It was immediately north of Kennett Square, Pennsylvania and was bordered on the west by the east Branch of the Red Clay Creek.

The test site was selected for the following reasons:

1. The site was underlain by metamorphic bedrock: the geologic materials were typical of those which extend from Washington, D. C. to Boston, Massachusetts.

2. The test site was located in a new landfill: the use of a virgin site permitted the obtaining of background chemical and physical data for both soil and water, which did not reflect any landfill pollution.

3. The test site was well above ground water: the soils and saprolite (weathered bedrock) were deep and well drained.

Climate Conditions

The field installation was located in the semi-humid northeastern part of the United States. Thirty-year monthly average precipitation and temperature data are given in Table 4.

Geology - Soils

Regional Geology

The southeastern Pennsylvania region is largely underlain by

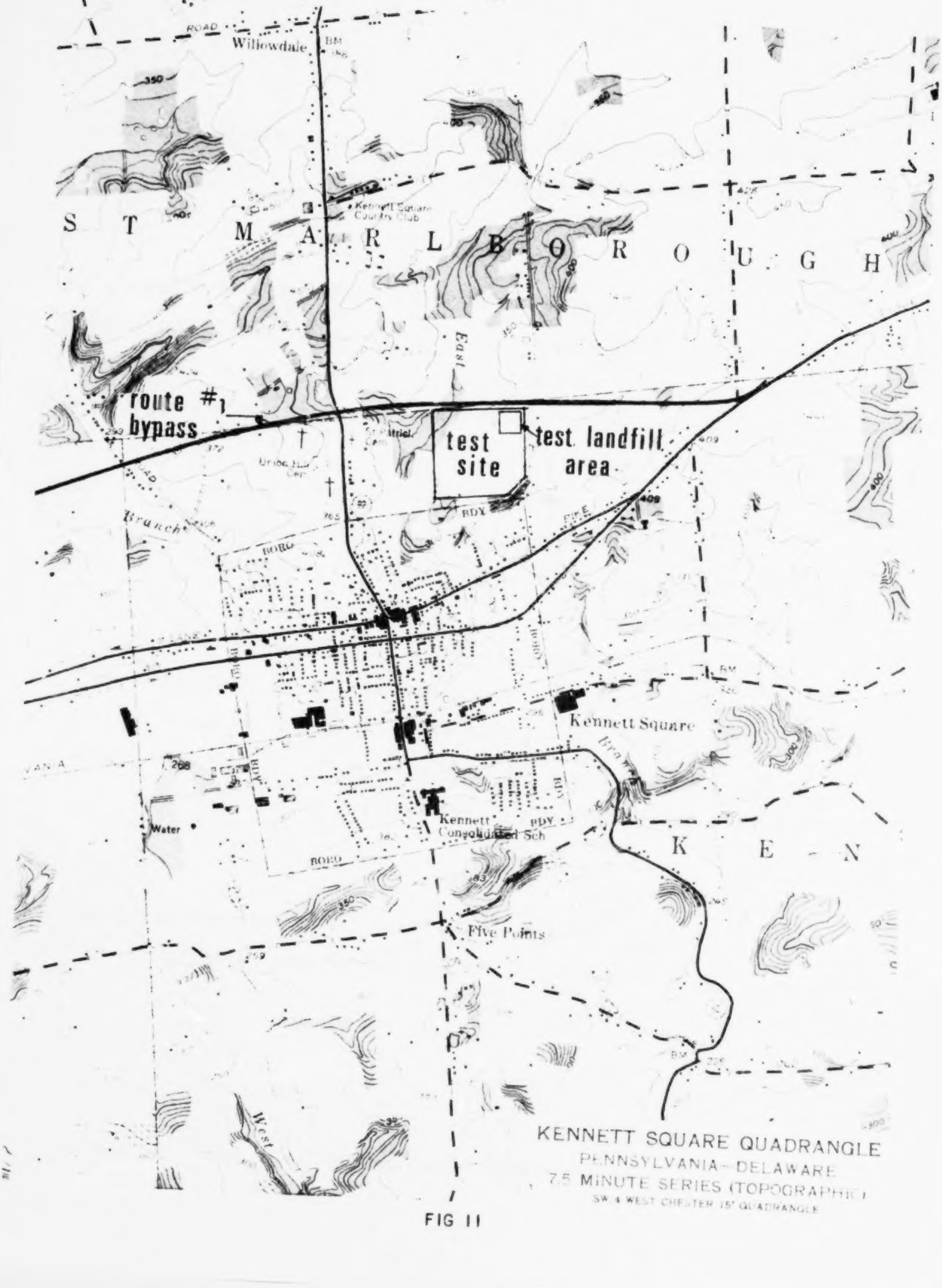

ROAD
Willowdale
BM
Kennett Square Country Club
S T M A R L B O R O U G H
East
route #1 bypass
test site
test landfill area
St. Patrick Cem
Union Hill Cem
Branch
BORO
RDY
PIKE
BDY
Kennett Square
Kennett Consolidated Sch
Water
K E N
Five Points
West
350
400
300
KENNETT SQUARE QUADRANGLE
PENNSYLVANIA—DELAWARE
7.5 MINUTE SERIES (TOPOGRAPHIC)
SW/4 WEST CHESTER 15' QUADRANGLE

FIG 11

TABLE 4

Thirty Year Average Precipitation and Temperature Data for Wilmington, Delaware

Thirty Year Average Precipitation

Month	Inches
January	3.40
February	2.95
March	4.02
April	3.33
May	3.53
June	4.07
July	4.25
August	5.59
September	3.95
October	2.91
November	3.53
December	3.03
Total	44.56

Thirty Year Average Maximum and Minimum Temperatures

Month	Maximum	Minimum	Average
January	41.3	25.2	33.4
February	42.4	25.2	33.8
March	50.5	32.0	41.3
April	62.5	41.6	52.1
May	73.4	52.0	62.7
June	81.8	61.0	71.4
July	86.2	65.8	76.0
August	84.2	64.3	74.3
September	77.9	57.3	67.6
October	67.3	45.9	56.6
November	55.1	35.7	45.4
December	43.5	26.7	35.1
Annual	63.8	44.4	54.1

Source: Department of Commerce, Weather Bureau the Wissahicken schist formation (Lower Paleozoic Age), granite gneiss and gabbroic gneiss and gabbro (Precambrian Age). These metamorphic rocks underlie the metropolitan region from Washington, D. C. to Boston, Massachusetts. These rocks are extensively faulted and have similar hydrogeologic characteristics. Bedrock is usually deeply weathered and highly decomposed resulting in a thick saprolite zone. The most common soils that develop in material weathered from this rock type belong to the Glenville, Chester, Glenelg and Worsham series.

The Glenelg series consists of moderately deep, well drained soils of uplands. The soils have moderate permeability and are better drained than the Glenville series. The Chester series consists of soils deep and well drained with moderate to moderately rapid permeability.

The Glenville series consists of deep, moderately well drained soils. They are on concave areas in the uplands and around the heads of streams, where the water table is high in the soil for long periods. Their permeability is moderately low.

The Worsham series consists of deep poorly drained soils of uplands. They have low permeability and are water-logged most of the time. They occur around seeps fed by springs at the heads of streams, along small streams, in slight depressions and along areas at the base of slopes.

Ground water is under water table conditions flowing from topographic highs to lows. The source of this ground water is rainfall that has infiltrated locally to recharge the ground water aquifers.

Site Geology

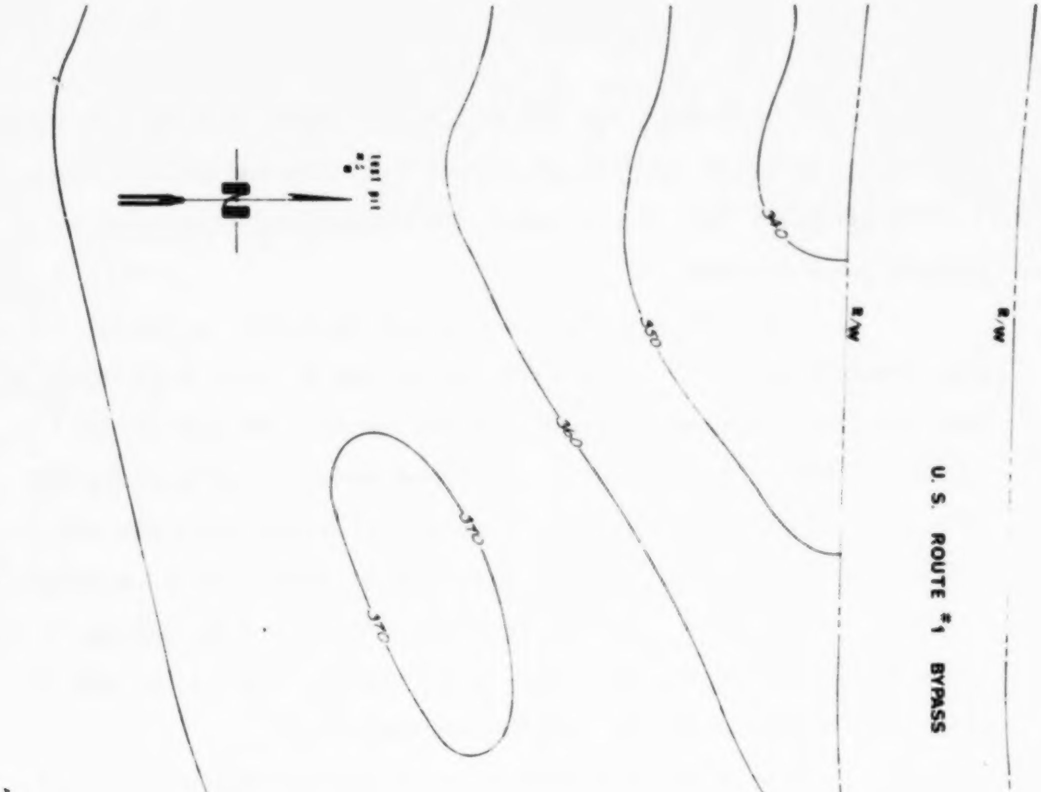
The site consists of a northeast, southwest drained topographic high with a range in elevation from 320 feet to 380 feet above mean sea level. The map location for this site is 11.5 inches west and 3.75 inches south of the northeast corner of the Kennett Square, Pennsylvania - Delaware 7 1/2 minute quadrangle. The portion of the quadrangle relative to this study is shown in Figure 11.

Ten soil identification pits were dug during the initial site investigation. Soil in these pits varied from 35 inches to 61 inches in depth overlying saprolite, a highly weathered bedrock. The general soil conditions consist of the Glenville and Worsham soils located below the 350 foot contour line and the Glenelg and Chester soil located above this elevation. The granite gneiss underlying the site is largely deeply weathered, micaceous, friable to compact, fine to medium bedded, has iron staining on joints and bedding planes, and is locally quartz-rich. Depth of bedrock is generally shallower on the crest of the topographic high.

A detailed description of two of the soil identification pits is adequate for the site. The approximate locations of these soil identification pits are indicated in Figure 12. The descriptions for these pits are given in Tables 5 and 6.

The direction of ground-water movement beneath most of the site is toward the southwest where it discharges into an unnamed tributary of the East Branch of the Red Clay Creek.

At the extreme northern edge of the site, ground-water movement is toward the highway cut for U. S. Route #1 Bypass. Ground-water movement at the western end of the site is toward the west to the East Branch Red Clay Creek, which flows in a southern direction. Two reservoirs for the Kennett Square water supply are present at the west end of the site between the stream and the landfill site. They are approximately 10 feet above the stream level and are hydrologically isolated from the ground water



TOPOGRAPHIC MAP OF KENNETT SQUARE LANDFILL SITE

FIGURE 12

TABLE 5

Test Pit No. 10

DEPTH (inches)	HORIZON	DESCRIPTION
0 - 13	AP	Dark-grayish brown silt loam, weak, fine and medium granular structure. Very friable. Non-sticky, non-plastic when wet, abrupt lower boundary. Range 10 inches to 15 inches.
13 - 20	B21	Strong (silt loam). Brown in color. Moderate medium - sub-angular blocky. Friable - non-sticky, non-plastic, granular wavy lower boundary. Thickness ranges from 5 inches to 9 inches.
20 - 25	B22	Yellowish brown loam, partial clay films, weak sub-angular blocky structure. Clear wavy lower boundary. Thickness ranges from 3 inches to 8 inches.
25 - 36	B3	Strong brown and yellowish brown loam, weak platy structure. Friable, non-sticky, non-plastic gradual wavy lower boundary. Thickness ranges from 10 inches to 16 inches.
36 - 60	C	Saprolite, very micaceous (biotite), dark gray/black, weathered to orange brown. Thin stringers of white micaceous deeply weathered feldspar. Gneissic bedding.
60 - 148		Deeply weathered, slightly micaceous saprolite. White, yellowish brown and manganese staining on bedding planes and joint surfaces. Saprolite is primarily a slightly micaceous feldspar with varying amounts of quartz. Clear quartz veins common. Weathered rock is incoherent to slightly coherent. Joints are closed. N60E - 315 feet.

TABLE 6

Test Pit No. 5

DEPTH (inches)	HORIZON	DESCRIPTION
0 - 9	AP	Dark grayish brown loam, very friable, non-sticky, non-plastic, abrupt smooth lower bound. Range 8 inches to 10 inches.
9 - 18	B21	Brown loam, very friable, weak sub-angular. Blocky structure, partial clay films, friable, non-sticky, non-plastic, 20 percent coarse fragments. Range ± 2 inches, 7 inches to 11 inches.
18 - 25	B22	Dark brown loam, friable, non-sticky, non-plastic, few clay films. Twenty percent coarse fragments lower bound. Abrupt, wavy. Range 5 inches to 9 inches, gradual wavy.
25 - 35	B3	Brown sandy loam, friable. Ten percent coarse fragments lower bound. Abrupt, wavy, non-sticky, non-plastic.
35 - 88	C	Lightgray, yellow brown and brown saprolite. Sandy. Range 60 inches to 88 inches at rock.
35 - 44		Deeply weathered granite gneiss, slightly micaceous, white, orange brown staining on bedding plane. Friable, scattered quartz veins.
44-49		Deep brown, very micaceous gneiss, deeply weathered, friable to compact.
49 - Rock		Saprolite, brown micaceous to very micaceous. Friable to compact, deeply weathered, long bedding planes.
Bedrock - Hole Depth, 120 inches		Granite gneiss, slightly micaceous, white to light gray, weathered along joints, fine to medium bedded. Thin quartz veins, thin zones of deeply decomposed rock, no open joints or bedding planes. 53 degrees South - North 60 East.

flow system. Southwestward drainage is present approximately 1/4 mile south of the site. The confluence of the unnamed tributary and East Branch Red Clay Creek is near the southwest corner of the site in the headwaters region of the creek.

There is one well, approximately 80 feet deep, in the vicinity of the landfill. It is located 321 feet east of the test landfill at a private residence. At this distance and location, it does not have any influence on the direction of ground water movement at the test landfill.

Test Pit Geology

The location of the test landfill is shown in Figure 13. The predominant soil type is a strong brown silt loam which is blocky, friable when moist, non-sticky and non-plastic when dry. It is of the Chester series marginal with Glenelg series. The bulk density of this soil falls within the range of 1.19 to 1.59. The average moisture held at 40 mm. tension is approximately 25 percent by weight. The permeability of these soils varies between 1.84 and 30×10^{-4} cm/sec. Using an average density of 91.4 lbs/ft^3 for undisturbed sub-strata and an average cation exchange data for the "C" horizon for Chester and Glenelg soils, the exchange capacity has been calculated to be 4,440 milligram equivalents/ft^3 of which 2,200 are hydrogen ions and the remainder metallic cations, mostly calcium and magnesium. This cation exchange capacity represents a considerable absorptive and renovating power. The extractible cations consist mainly of calcium.

Air rotary drill borings were made to determine subsurface conditions and to install the various sampling tubes. On the basis of three borings (nos. 8, 10, 11; Fig. 13), in the immediate vicinity of the test landfill, the following geological conditions were found to exist: three feet of field silt loam soil overlying 33 feet to 37 feet of a soil micaceous

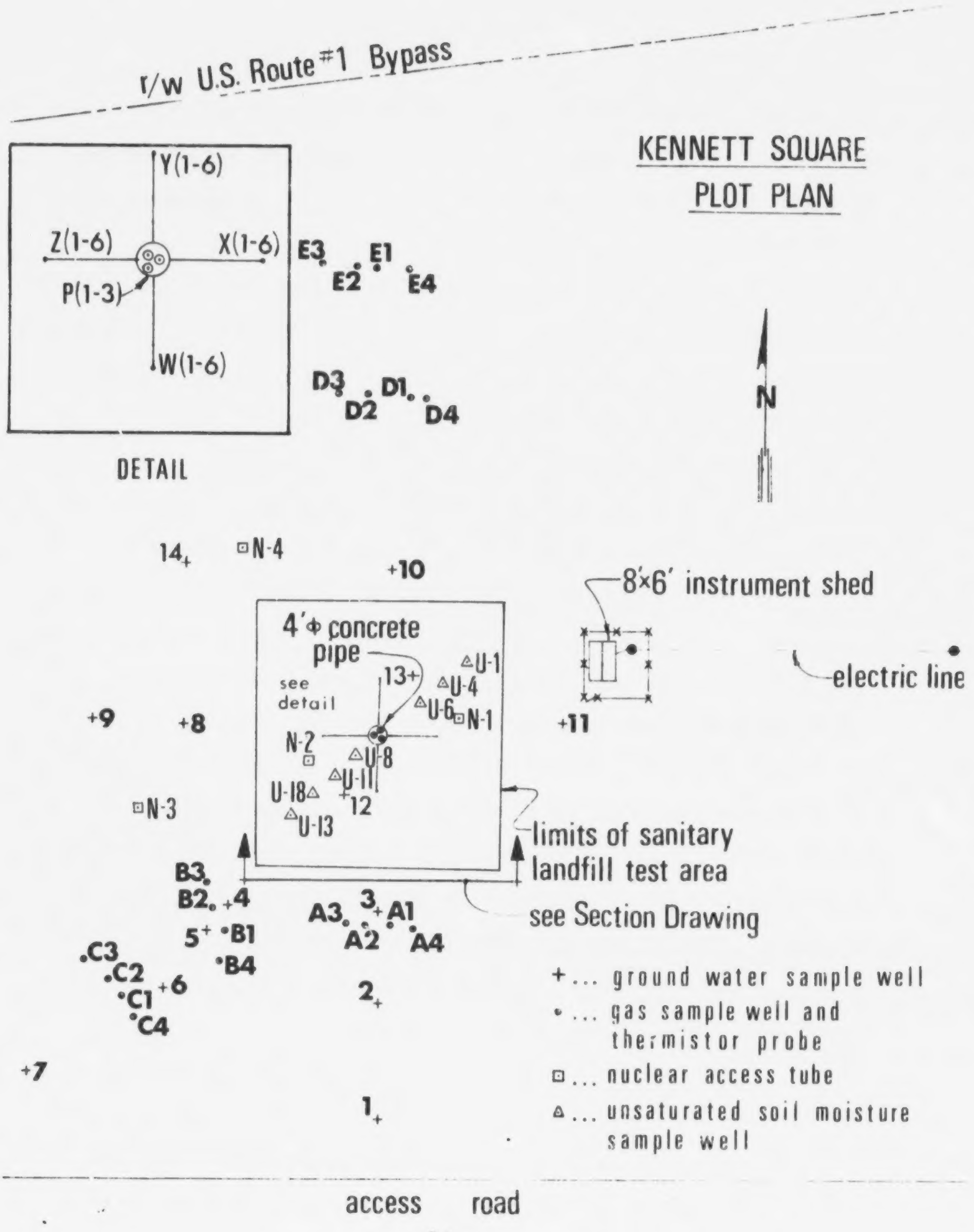

r/w U.S. Route #1 Bypass
KENNETT SQUARE
PLOT PLAN
Y(1-6)
Z(1-6)
X(1-6)
P(1-3)
W(1-6)
DETAIL
E3
E1
E2
E4
D3
D1
D2
D4
N
14
N-4
+10
4'Φ concrete pipe
see detail
13+
U-1
U-4
U-6
N-1
+9
+8
+11
N-2
U-8
U-11
U-18
12
U-13
N-3
8'×6' instrument shed
electric line
limits of sanitary landfill test area
see Section Drawing
B3
B2
+4
3
A3
A1
A2
A4
5+
B1
B4
C3
C2
+6
C1
C4
2
+7
1
+ ... ground water sample well
• ... gas sample well and thermistor probe
▫ ... nuclear access tube
△ ... unsaturated soil moisture sample well
access road

fig 13

gneiss bedrock.

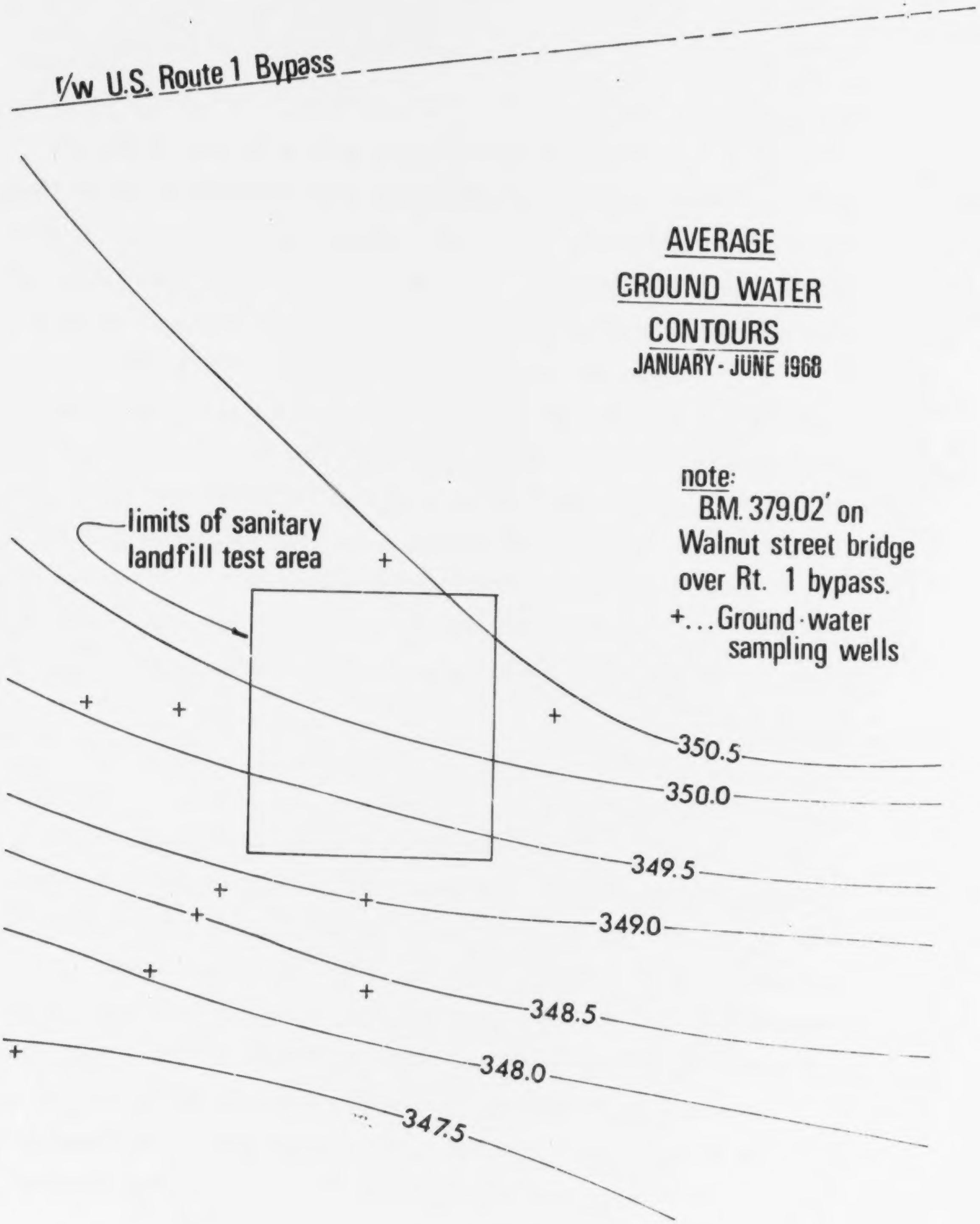
Samples of the saprolite were taken in the base of the test pit. The typical saprolite, which comprises about 75 percent of the pit floor is micaceous with abundant feldspar and a moderate amount of quartz. Approximately 20 percent of the area is a predominantly quartz-rich saprolite, and approximately 5 percent of the area is an iron- and manganese-rich saprolite.

Ground water was encountered at depths of 20 feet to 22 feet in the 11 borings around the test landfill. The direction of ground-water movement is to the southwest with a gradient of approximately 1/2 foot in 20 feet (Fig. 14). The test site is located so that ground-water movement is away from the site and is not affected by adjacent landfilling operations. Water levels showed a slight rise from November 11, 1967 to March 11, 1968 of 0.3 feet to 0.5 feet. Spring recharge took place between March 11, 1968 and May 10, 1968 as water levels rose approximately 1 foot to 1.5 feet.

Site Plan

The general topography of the site and the parcel used for this study are shown in Figure 12. In general, the northeastern end of the site (the test landfill location) has a relatively gentle slope. Toward the northwestern end of the site, the ground surface falls sharply toward U. S. Route #1 Bypass. This change in topography is not considered significant because the test area is approximately 500 feet removed from the slope.

Details of the portion of the site instrumented for this study are shown in Figure 13. Preliminary instrumentation began in the summer of 1967. At that time, a 50 foot by 50 foot by 10 foot deep pit was excavated and instrumentation was initiated.



AVERAGE
GROUND WATER
CONTOURS
JANUARY - JUNE 1968

note:
B.M. 379.02′ on
Walnut street bridge
over Rt. 1 bypass.
+...Ground water
sampling wells

fig 14

Upon completion of the filling operation (described later) in May of 1968, the ground surface of the test area was contoured so as to retain all precipitation on the 50 foot by 50 foot fill area and to prohibit area inundation by any external surface water.

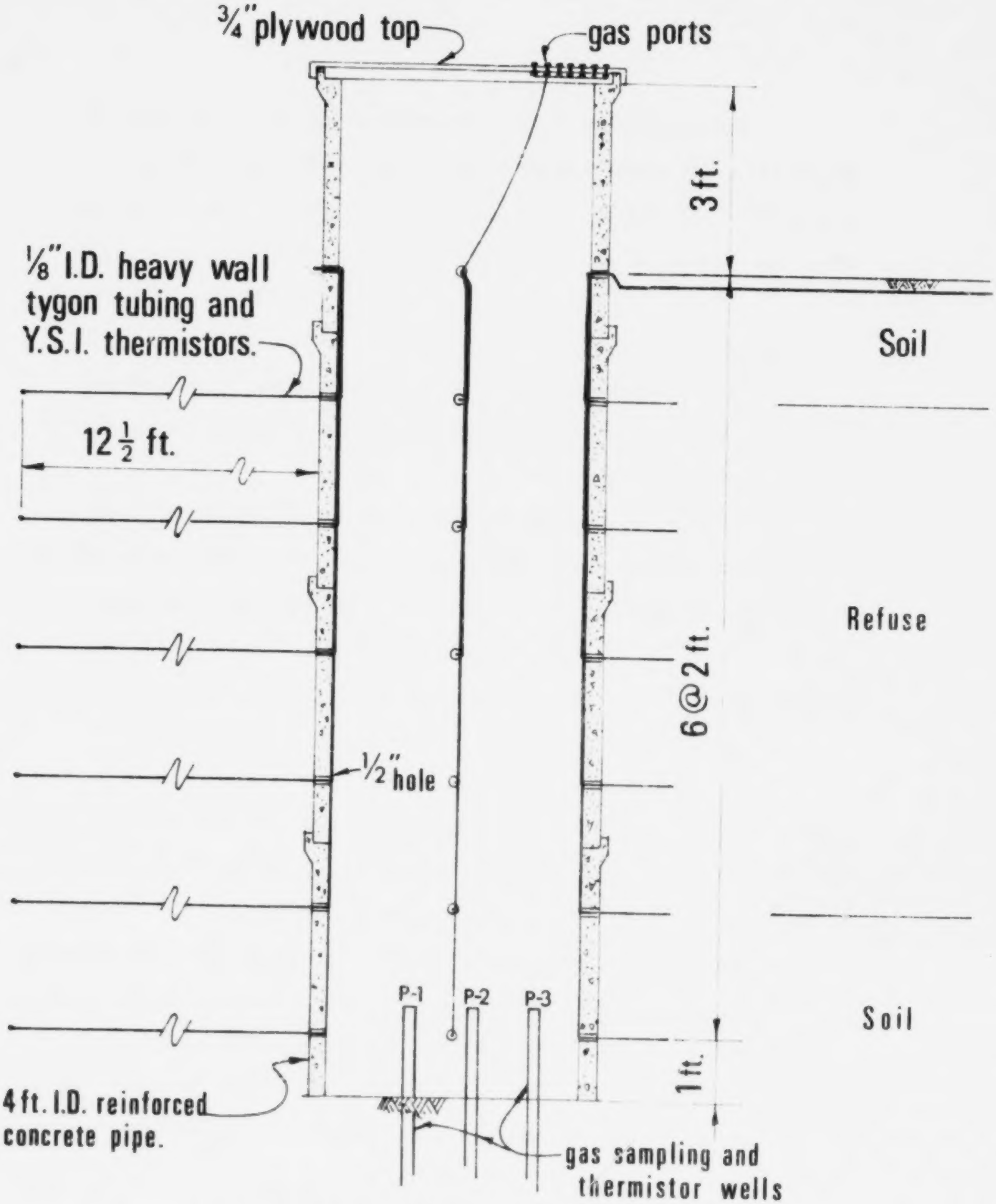
Instrumentation

Basic instrumentation of the site was similar to that of the laboratory lysimeter. Instrumentation began in the Fall of 1967 after excavation of the test pit.

A four-foot diameter concrete pipe was located in the center of the test pit. This concrete pipe served as a hub from which all horizontal instrumentation extended into the test pit. The location of the pipe is shown in Figure 13, and a cross-section is shown in Figure 15. A cross-section through the entire fill area is shown in Figure 16.

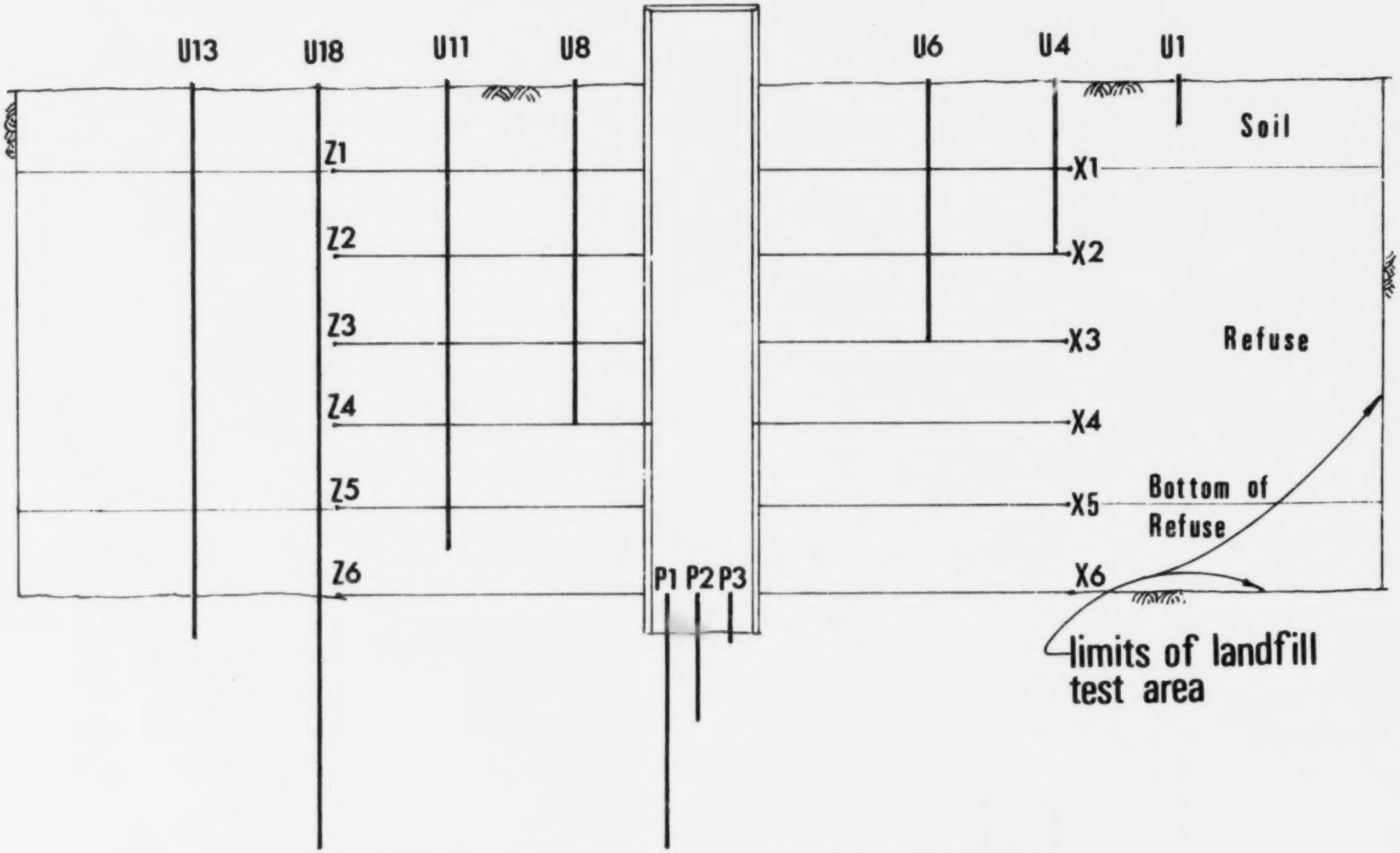
Gas Samples

Gas samples were taken through tubes located within the fill and at various locations in the in-situ earth material above the water table. Locations were chosen so as to monitor gas and temperature changes both horizontally and vertically inside, outside and beneath the test landfill. Lateral sampling tubes extended from the center concrete pipe into the test landfill. Vertical sampling tubes extended from the ground surface to the various sampling depths. Tube locations are shown in Figure 13. Series A through E and P designate clusters of vertical gas tubes. Series W through Z designate the lateral gas tubes. Sampling depths are summarized in Table 7.


¾" plywood top
gas ports
3 ft.
⅛" I.D. heavy wall tygon tubing and Y.S.I. thermistors.
Soil
12 ½ ft.
Refuse
6@2 ft.
½" hole
P-1
P-2
P-3
Soil
1 ft.
4 ft. I.D. reinforced concrete pipe.
gas sampling and thermistor wells

CROSS SECTION OF CONCRETE PIPE

fig 15



KENNETT SQUARE PLOT SECTION DRAWING

fig 16

TABLE 7

Sample Depths - Gas and Temperature for Field Facility

Series	Number	Depth Below Original Ground Surface
A through E	1	4 feet
	2	8 feet
	3	13 feet
	4	18 feet
P	1	13 feet
	2	15 feet
	3	18 feet
W through Z	1	2 feet
	2	4 feet
	3	6 feet
	4	8 feet
	5	10 feet
	6	12 feet

Location of Three Additional Temperature Units

1. Water Well No. 11 - Monitors Ground Water Temperature.
2. Instrument House - Monitors Air Temperature.
3. Six Feet west of instrument house, three inches below soil surface - monitors soil temperature.

Figure 17 is a schematic of a gas sampling tube and thermistor well. The wells were placed using a four inch rotary drill. Each hole was predrilled and then instrumented using the following sequence:

1. Six inches of 1/8 inch to 1/2 inch gravel was placed at the bottom of the hole.

2. Rigid 1 1/4 inch I.D. plastic pipe containing predrilled holes and a neoprene stopper was inserted into the hole. The gas sample tube and thermistor were inserted into and sealed in the stopper. The neoprene stopper was positioned in the tube at the terminal point of the drilled holes. The stopper was sealed in the tube to prevent gas leakage.

3. After pipe insertion, an additional 12 inches of gravel were placed around the exterior of the pipe.

4. A coarse to fine sand pack was placed on top of the gravel to a depth of approximately 5 feet.

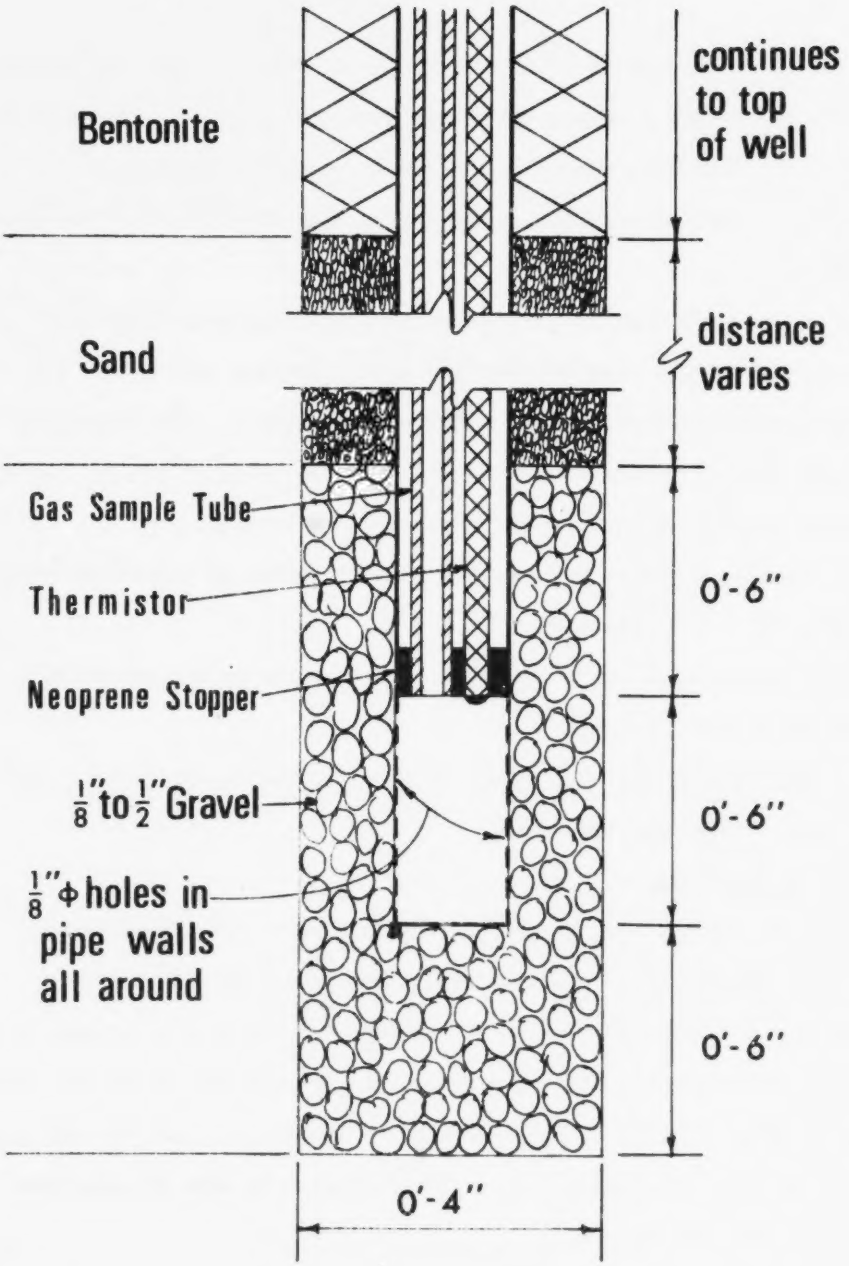
5. The distance from the top of the sand to the ground surface was tightly sealed with Bentonite clay.

Temperatures

Temperatures were monitored once every four hours by an automatic scanning-printing system using thermistors and a digital thermometer. The thermistors were positioned at 50 locations throughout the test area. Forty-seven temperature locations corresponded to the gas sample positions listed in Table 7. The three other thermistor locations are also listed in Table 7. The method of installation was the same as described previously under gas samples.

Ground Water Samples

Fourteen ground water observation wells drilled approximately 10 feet below the ground water table were located over the site. Their loca-



DETAILS OF GAS SAMPLING AND THERMISTOR WELLS

fig 17

ations are shown in Figure 13.

The ground water wells were located so as to be in the direction of ground water movement, which was predetermined by installation of pilot wells prior to excavation of the main test pit.

The wells consisted of 1 1/4 inch I.D. semi-rigid plastic pipe placed in a 5 1/2 inch diameter drill hole. The pipes were 35 feet long and had 1/8 inch diameter holes drilled along the bottom 9 feet. The volume of the drill hole exterior to the pipe was gravel packed (1/8 inch to 1/4 inch gravel) to a distance of 1 foot above the top of the holes. The remaining volume of the space was filled with Bentonite clay to within five feet of the soil surface. From the top of the Bentonite to the ground surface, native soil was used to complete the seal.

The sealing procedure insured free passage of suspended solids into the wells, but prohibited entrance of surface water.

Unsaturated Soil Water Samples

Water samples were obtained from the soil above the water table and in the refuse by using a soil moisture sampler (Soil-Water Sampler - Soilmoisture Equipment Company, Goleta, California; catalog no. 1900).

The sampler contained a "1 bar entry value" porous ceramic cup inserted at the end and cemented to a 1.9 inch I.D. plastic pipe. The open end of the pipe was fitted with a rubber stopper which had provision for application of a vacuum.

Method of placement was the same as for the gas sampling tubes.

Soil Moisture and Density Measurement

Four stainless steel access tubes, 1 5/8 inches, I.D., and 0.35 inch wall thickness were located within the landfill and the adjacent undisturbed soil. Each tube was 18 feet long. These tubes permitted the measurement of in-situ moisture and density. The location of these tubes is shown in Figure 13.

The moisture and density measurements were performed periodically at two-foot depth increments below the ground surface using a Nuclear Chicago Model P14 Depth Moisture Gauge and a Model P20 Depth Density Gauge.

Raingauge

A Belmont No. 551 recording raingauge was located on top of the instrument shed. The location of the instrument shed is shown in Figure 13.

Rain data was recorded continuously on a strip chart controlled by a spring-operated seven-day clock movement.

Instrumentation Schedule

Inside the Test Landfill Area

The P series gas and temperature units were emplaced after the concrete hub was positioned and prior to the filling operation.

During the filling operation, the tygon lateral gas and temperature units, series W through Z, were located in the fill at the selected depths. The lateral units were extended to a distance of 10.5 feet from the face of the concrete hub at each level in each of the four compass directions. After each two feet of refuse was emplaced, trenches were dug for each unit and then backfilled by hand. This procedure insured against injury during the refuse emplacement.

After completion of the filling operation, the two ground water observation wells beneath the landfill area were drilled. Their method of emplacement followed the procedure previously described. Also installed at this time were the unsaturated soil moisture sampling devices and the 1 5/8 inch I.D. standard steel tubes for use in the in-situ moisture and density determinations.

Outside the Test Landfill Area

All observation wells, except for the pilot ground water observation wells, were emplaced at the same time as the P series gas and temperature units. The pilot ground water observation wells were established approximately six months prior to excavation of the test pit to permit adequate determination of the direction of ground water movement.

Sample Analysis

Gas Samples

Samples were obtained weekly and analyzed for carbon dioxide, oxygen, nitrogen, methane, hydrogen sulfide and carbon monoxide using a gas chromatograph. The sampling technique and analytical procedures are described in Appendix 1.

Ground Water Samples

Samples were obtained weekly. The analyses performed are listed in Table 2. Analytical procedures are described in Appendix 1.

To obtain samples from the shallower wells, a vacuum system was used. A pump, located in the instrument house, was attached to tygon tubing which was lowered into each well to a depth of 25 feet. The pump was then turned on and the sample was collected in a liter flask and transferred to the sample bottles.

To obtain samples below 28 feet, a Clayton-Mark sand pump with 3/4 inch I.D. tygon tubing was used. The sand pump operated on the same principle as a bailing bucket with a ball bearing in its housing. As the pump was lowered into the well, the water raised the ball bearing, opening the entrance port. Then, when the pump was pulled from the well, the ball fell back into placed and then closed the port. The sampling method insured a representative sample with no filtering.

Unsaturated Soil Moisture Samples

A vacuum was applied to the upper end of each tube for a time sufficient to obtain an adequate amount of sample (determined experimentally).

The soil moisture samples accumulated in the bottom of the tube above the porous ceramic cup. They were removed from the tube by a small pump. The samples were analyzed for the same pollutants as the ground water samples.

Soil Moisture and Density Determination

The testing procedure was as established by Nuclear-Chicago for using their equipment in soils. A brief summary of the procedure is given in Appendix 4.

Refuse Placement

The filling of the test area began on April 29, 1968 and was completed on May 14, 1968. The trench method of sanitary landfilling with horizontal compaction was used. At the end of each day's operation, the refuse was covered with approximately six inches of soil.

Refuse and daily soil cover were compacted at natural moisture content. The compaction equipment was a Caterpillar Front End Loader, Model No. 955K. This model weighed approximately 16.5 tons and produced a contact pressure of about 7 pounds per square inch.

The refuse used was primarily domestic with a small percentage of industrial, mainly plastics and cardboard. Collection trucks were primarily compacter type with 16 to 20 cubic yard capacities. During the filling operation, gross and net weight of each truck was obtained to compute refuse weights and densities. Incoming densities ranged from a minimum of 150 pounds per cubic yard to a maximum of 700 pounds per cubic yard. Average density was 500 pounds per cubic yard.

Total weight of emplaced refuse was 274 tons. Neglecting the 6 inch daily soil cover, the compacted density of the fill was 740 pounds per cubic yard for a compaction ratio of 1.5 to 1.

The estimated total thickness of intermediate soil covers used at the end of each day's filling was 1.4 feet. Using a net height of 6.6 feet for refuse gave an adjusted initial unit weight of 895 pounds per cubic yard.

A random sampling technique was used to obtain representative refuse samples. The chemical composition of the emplaced refuse, based on these composite samples, is given in Table 8.

Photographs

Photographs of the field experimental facility and its installation are given in Appendix 3.

EXPERIMENTAL RESULTS

Sanitary Landfill Laboratory Lysimeter

Experimental data are reported for the period October 1, 1967 to August 31, 1969. Under a grant extending this study, data is still being collected beyond the period covered by this report. The data have been

TABLE 8

Field Refuse Chemical Composition*

Ash	20.2 percent
Free carbon	0.57 percent
Crude fiber	38.0 percent
Moisture content	26.6 percent
Hardness	2.67 mg/gram
Phosphate	0.01 mg/gram
Sulfate	2.72 mg/gram
Chloride	0.41 mg/gram
Sodium	0.62 mg/gram
Nitrogen	
a) ammonia	0 mg/gram
b) organic	.02 mg/gram
COD	1.32 mg/gram
Major Metals:	
Aluminum, Calcium, Iron, Silicon, Sodium	>5 percent**
Minor Metals:	
Magnesium, Titanium	1-5 percent**

*Preliminary results (digested 8 hours).

**Emission spectroscopy of non-volatile portion.

tabulated in Volumes 2 and 3 and are summarized in graphical form in this section.

Figure 18 represents the volume of water added at the top of the lysimeter and the leachate removed at the bottom. Given in Figure 19 is the curve for the water stored in the lysimeter (amount added minus quantity of leachate). Leachate pH values are presented in Figure 20. Curves representing the concentrations of the various ions, hardness, COD, suspended and total dissolved solids are presented in Figures 21 through 33.

Curves of total iron, zinc, phosphate, sulfate, chloride, sodium, nitrogen (ammonia), nitrogen (free), hardness, chemical oxygen demand, suspended solids, nickel and copper removed are presented in Figures 34 through 46.

Leachate Quantity

The curves in Figure 18 show the influence of initial water content and the programmed water feeding schedule on leachate production. The curves graphically indicate the initial lag between water addition and leachate production.

The generation of substantial quantities of leachate required that each lysimeter component be at their respective field capacities. The soil cover, refuse and Ottawa sand-glass bead bed were placed in the lysimeter in a relatively dry state. As a result, a major portion of the water initially added was adsorbed by each component until they reached their respective field capacities. This adsorption was the cause of the difference between the two curves during the early portion of the test period. It is noteworthy that within one week after the initiation of the test, a small amount of leachate was obtained.

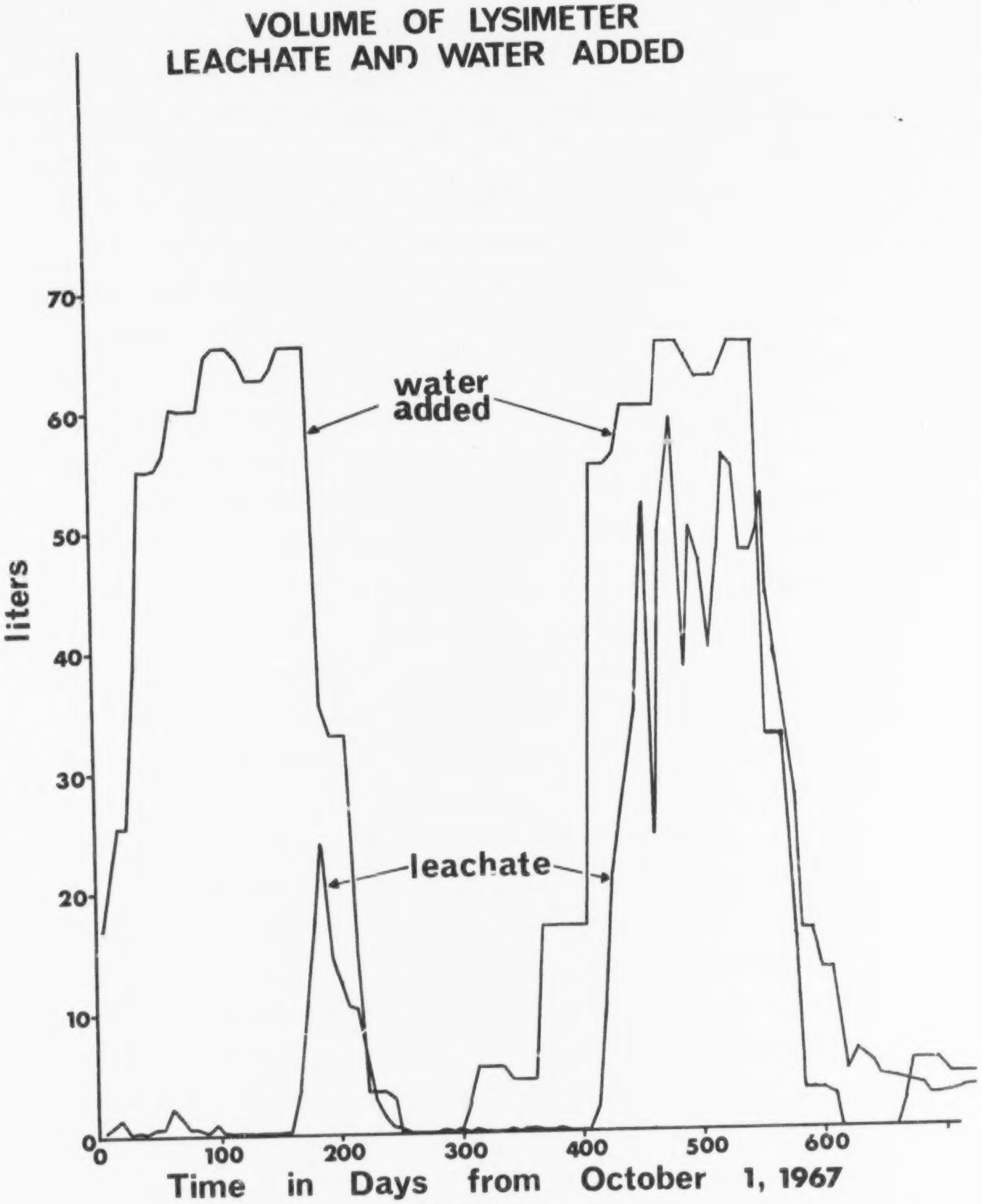

VOLUME OF LYSIMETER
LEACHATE AND WATER ADDED
liters
0
10
20
30
40
50
60
70
0
100
200
300
400
500
600
water
added
leachate
Time in Days from October 1, 1967

FIGURE 18

As the net quantity of water stored in the lysimeter increased (Figure 19), leachate production increased. A significant amount of leachate began to be produced by the lysimeter at approximately 430 days into the test. However, field capacity was not attained until the end of the time period covered by this report.

The phase relationship between water added and leachate production is also evident from the curves. Even during periods of low leachate production, any decreases in water input further reduced or eliminated leachate. On the other hand, as water input increased, leachate production also increased.

Leachate production can be attributed to one or all of the following sources:

1. FROM THE REFUSE

   Most of the initial leachate is obtained from the refuse organic components and initial moisture content by the compaction and placement procedure.

2. FROM CHANNELING

   Some of the water added at the top of the lysimeter finds a direct route through the refuse to the collection trough, due to any refuse inhomogeneities.

3. FROM AN ADVANCED WETTING FRONT

   The wetting front in the refuse moves as a broad band rather than as a single-line interface. As a result, substantial increases in leachate occur before the entire system is at field capacity.

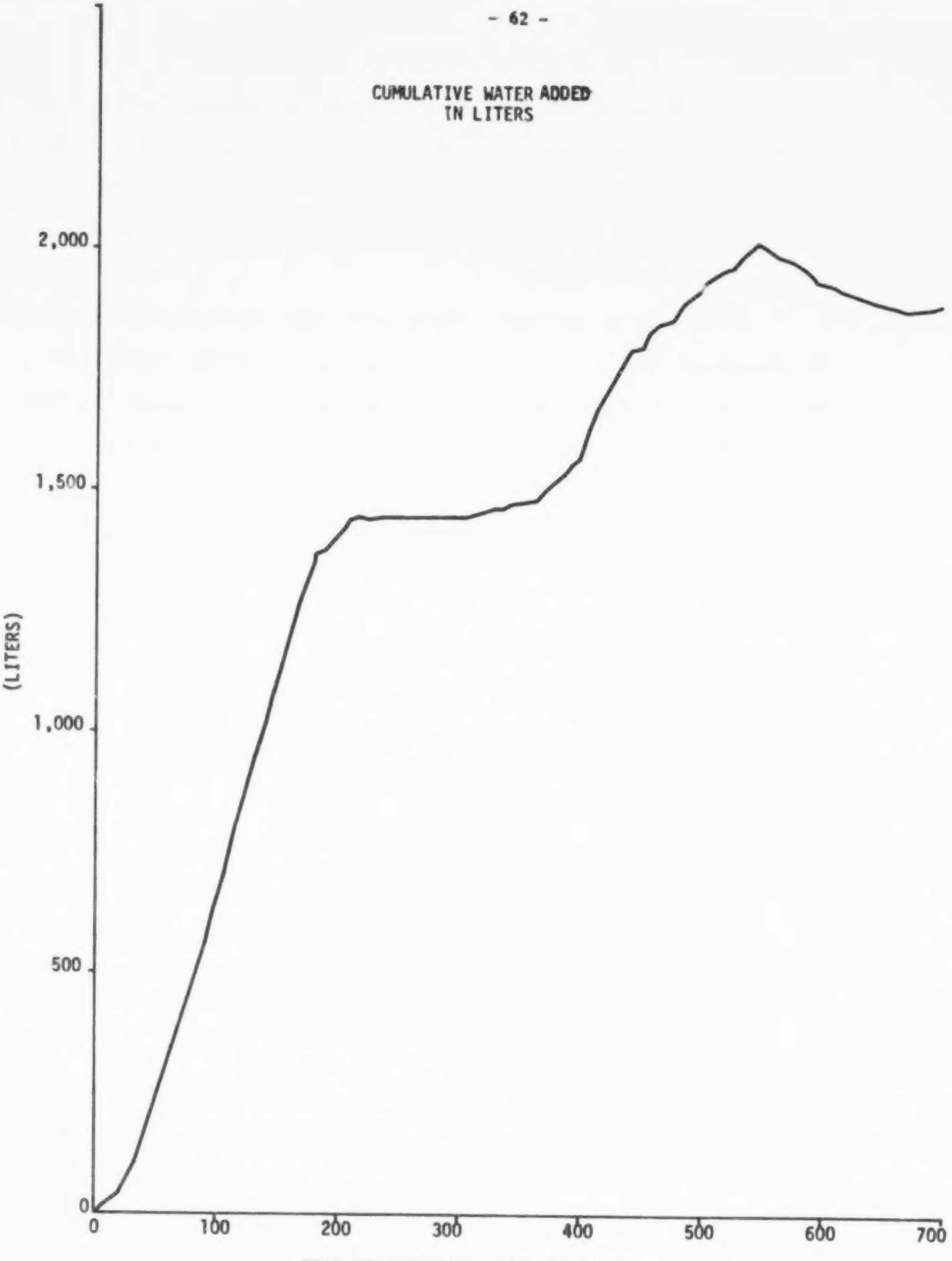

CUMULATIVE WATER ADDED
IN LITERS
(LITERS)
2,000
1,500
1,000
500
0
0
100
200
300
400
500
600
700
TIME IN DAYS FROM OCTOBER 1, 1967

FIGURE 19

4. FROM THE MAIN WETTING FRONT

> This is the leachate produced
> when the system reaches field
> capacity. At this stage, input
> water and leachate quantities
> become approximately equal.

From the curves presented in Figures 18 and 19, it may be concluded that sources 1 and 2 were responsible for the leachate collected during the early time period. Their influence on leachate collected during the latter time periods was negligible. Between 175 and 210 days, leachate production increased substantially. However, the amount of leachate produced was significantly less than the input water quantities. This behavior pattern can best be described by the one outlined as source 3. Finally, in the second year, leachate quantity increased to a level almost equal to input water quantities. This behavior indicated that the entire system was at about field capacity, and that a transition between source 3 and source 4 was occurring. Full field capacity, hence, source 4, was attained at the end of the period covered by this report.

Patterns of Leachate-Pollutant Generation

pH

The curve in Figure 20 shows that wide variations in pH occurred during the test period. Generally, solutions were acidic with a mean pH value of approximately 5.5.

Comparison of Figures 18 and 20 indicates that leachate pH bears a relationship to leachate quantity. From the curves it appears that highly

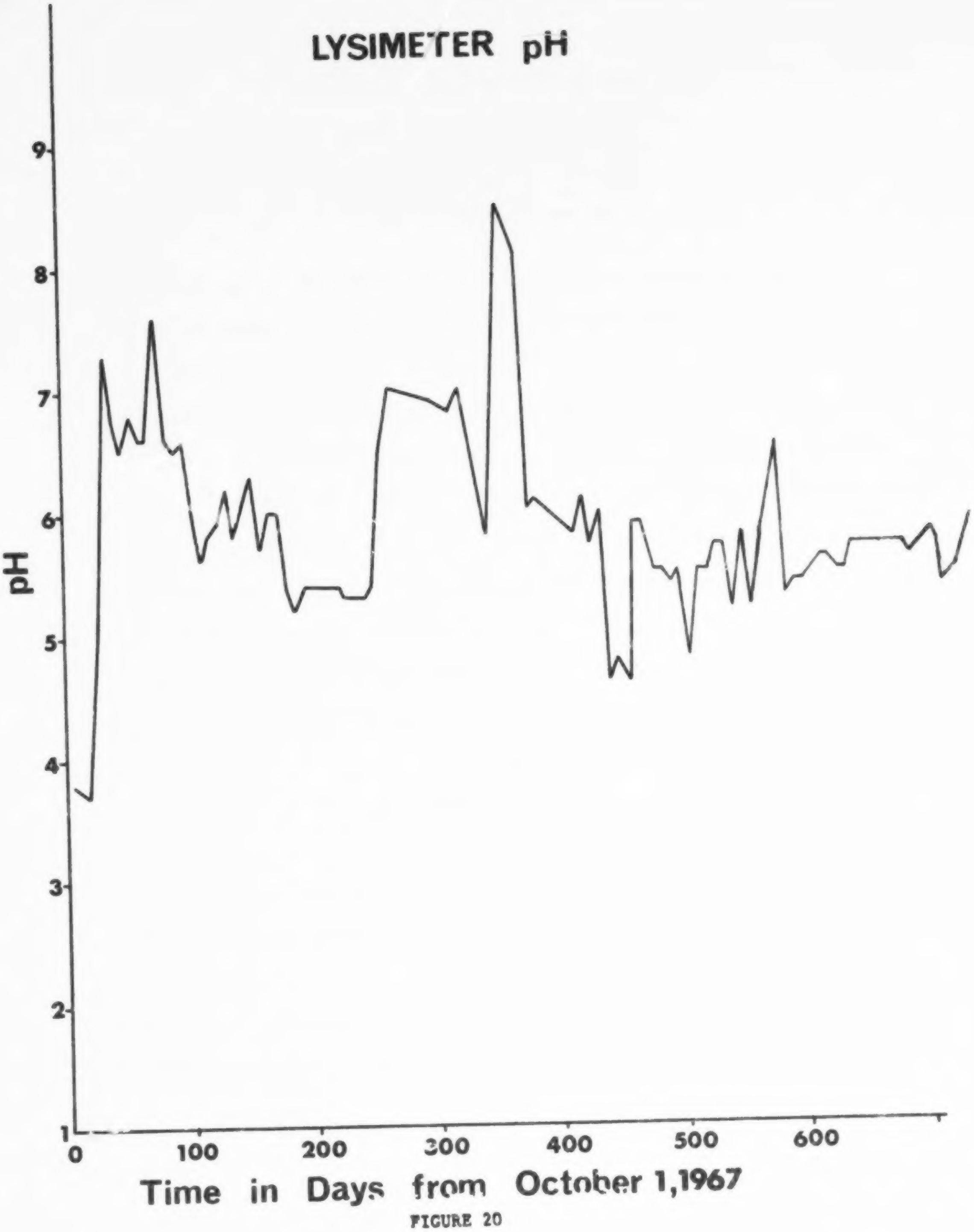

LYSIMETER pH
pH
1
2
3
4
5
6
7
8
9
0
100
200
300
400
500
600
Time in Days from October 1,1967

FIGURE 20

erratic pH values correspond to periods of low leachate production and that pH values between 5 and 6 correspond to periods of high leachate production.

It is believed that flow rate through the refuse is a major controlling factor in establishing leachate pH, and that with high flow rates, the pH will generally be acidic.

Generation of large quantities of acidic leachate compound the potential pollution problem, because low pH values reduce exchange capacities of renovating soils at the time when quantities are high.

Iron

The curve for iron concentration is presented in Figure 21. A comparison of Figure 21 with the leachate volume curve (Fig. 18) indicates that leachate volumes had a significant influence on iron concentration.

During low leachate flow periods, iron concentrations were low, whereas, when leachate quantities were high there was a significant increase in iron concentrations. This behavior pattern may be explained by the fact that during periods of low leachate volume, solution pH exceeded 5.5 and during periods of high leachate volume, solution pH was less than 5.5. Below a pH of 5.5, many iron salts, both ferric and ferrous, are soluble. Because of their ability to remain in solution, they are more easily removed from the refuse. Above a pH of 5.5, iron salts are less soluble, will precipitate and be filtered from the leachate by either the refuse or underlying materials.

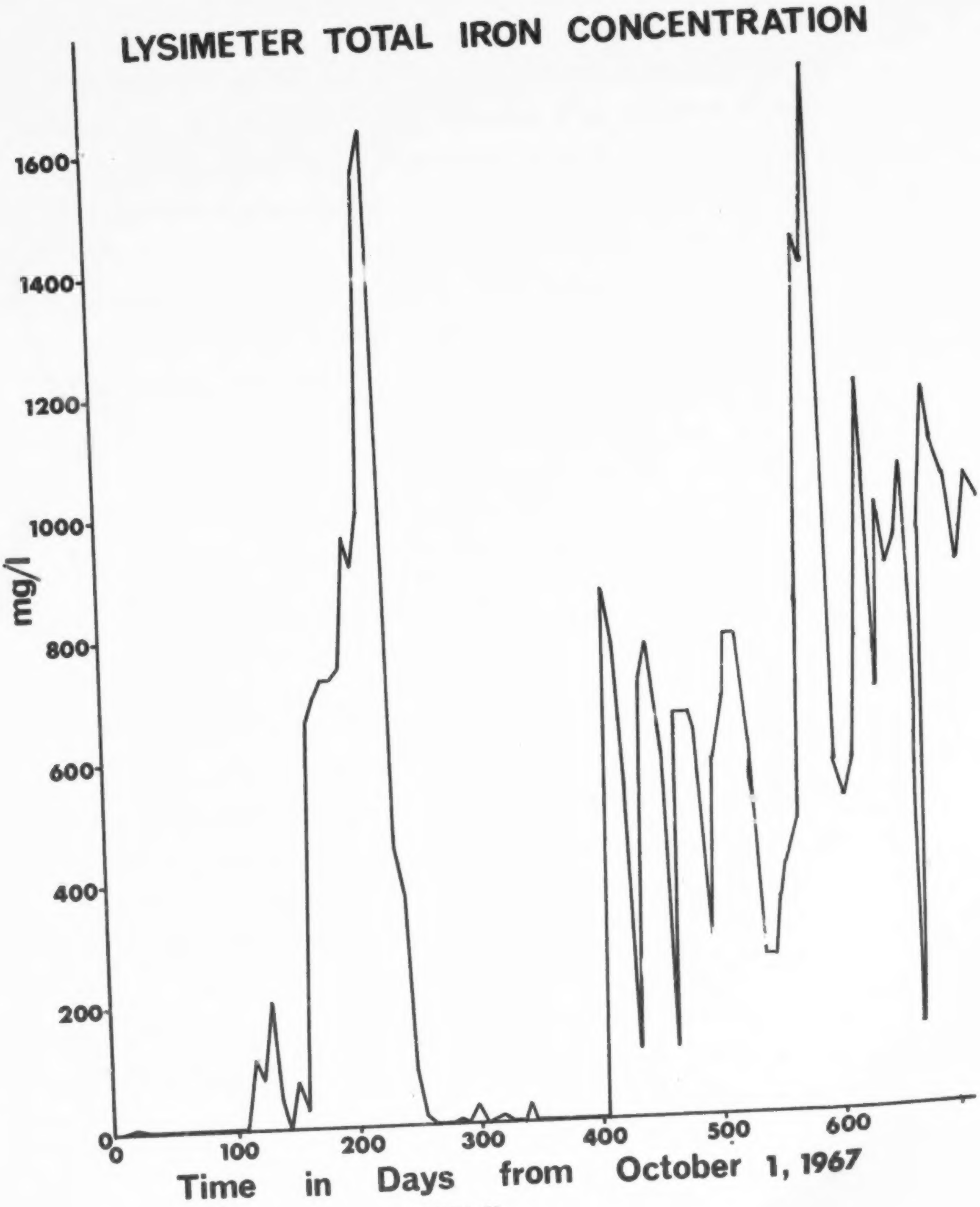

LYSIMETER TOTAL IRON CONCENTRATION
mg/l
1600
1400
1200
1000
800
600
400
200
0
0
100
200
300
400
500
600
Time in Days from October 1, 1967

FIGURE 21

Iron concentrations were in excess of 1600 mg/l during both periods of high leachate volume. Figure 34 summarizes graphically the total iron which was removed during the test period. At the end of the test period, a total of approximately 830 grams of iron had been removed.

Zinc

Leachate zinc concentrations are presented in Figure 22. Significant increases in zinc concentrations occurred after one and one third years of testing. Initial concentrations were as high as 120 to 135 mg/l. More usual concentration levels were between 15 and 30 mg/l.

After the first appearance of zinc, it was in all leachate samples. This pattern indicated the release of the zinc ion due to the breakdown of some refuse component which previously had resisted the leaching action. As shown in the accumulative zinc curve, Figure 35, approximately 50 grams had been removed by the end of the test period.

Phosphate

The curve for leachate phosphate concentration is shown in Figure 23 and the accumulative phosphate curve in Figure 36.

Concentration levels reached 130 mg/l during the initial period of the test. Thereafter, concentration levels were markedly lower and irregular. While recorded values were usually less than 5 mg/l, 30 mg/l peaks occurred at 100 and 600 days. A total of 3.8 grams were removed during the test period with most of this removed during the last 60 days.

Sulfate

The curve for sulfate concentration is presented in Figure 24 and the accumulative sulfate curve is presented in Figure 37.

Initial values of sulfate ion concentrations were 250 mg/l. After a decrease to between 25 and 75 mg/l at approximately 100 days, they

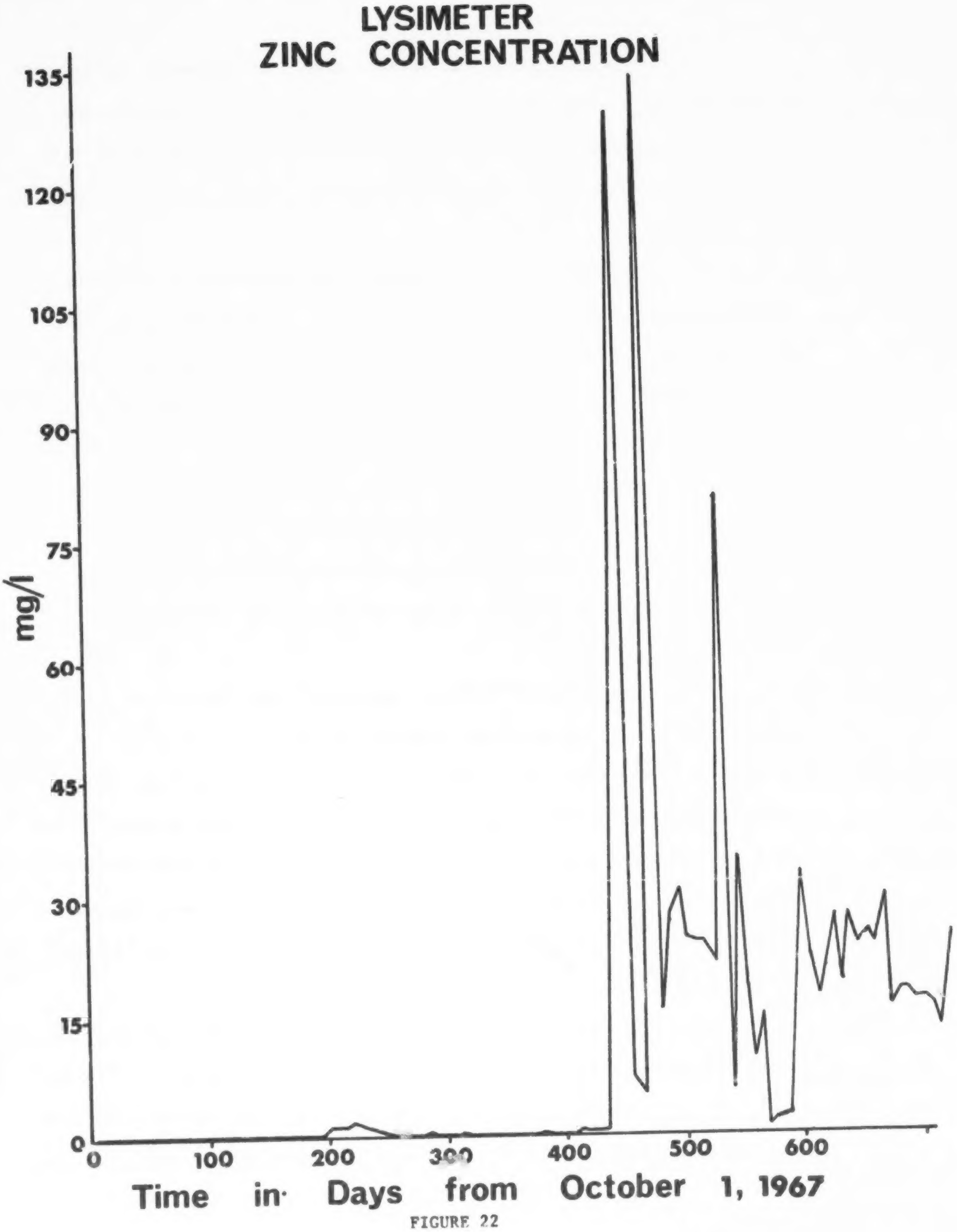
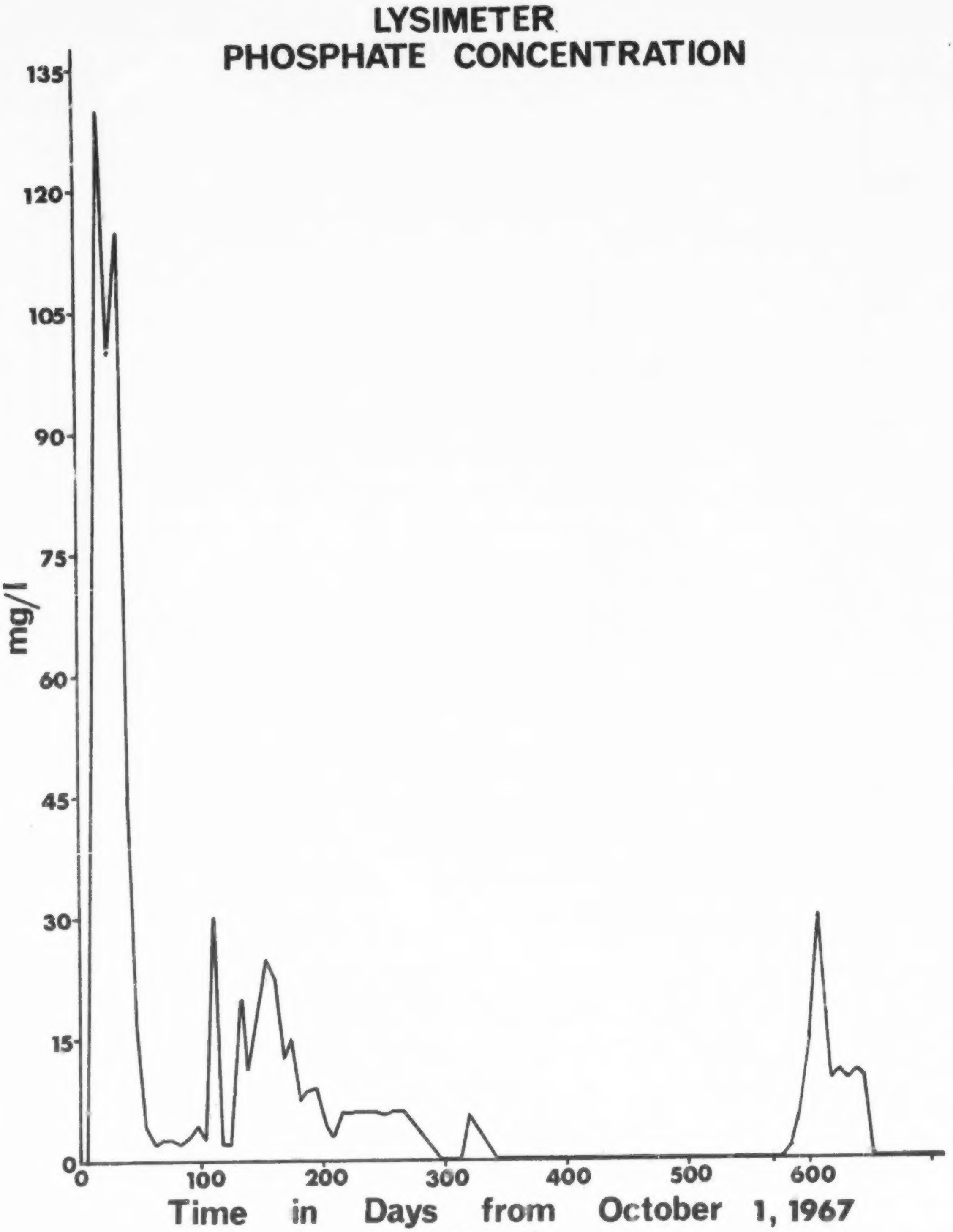

LYSIMETER
ZINC CONCENTRATION
mg/l
135
120
105
90
75
60
45
30
15
0
0
100
200
300
400
500
600
Time in Days from October 1, 1967

FIGURE 22



LYSIMETER
PHOSPHATE CONCENTRATION

FIGURE 23

LYSIMETER
SULFATE CONCENTRATION

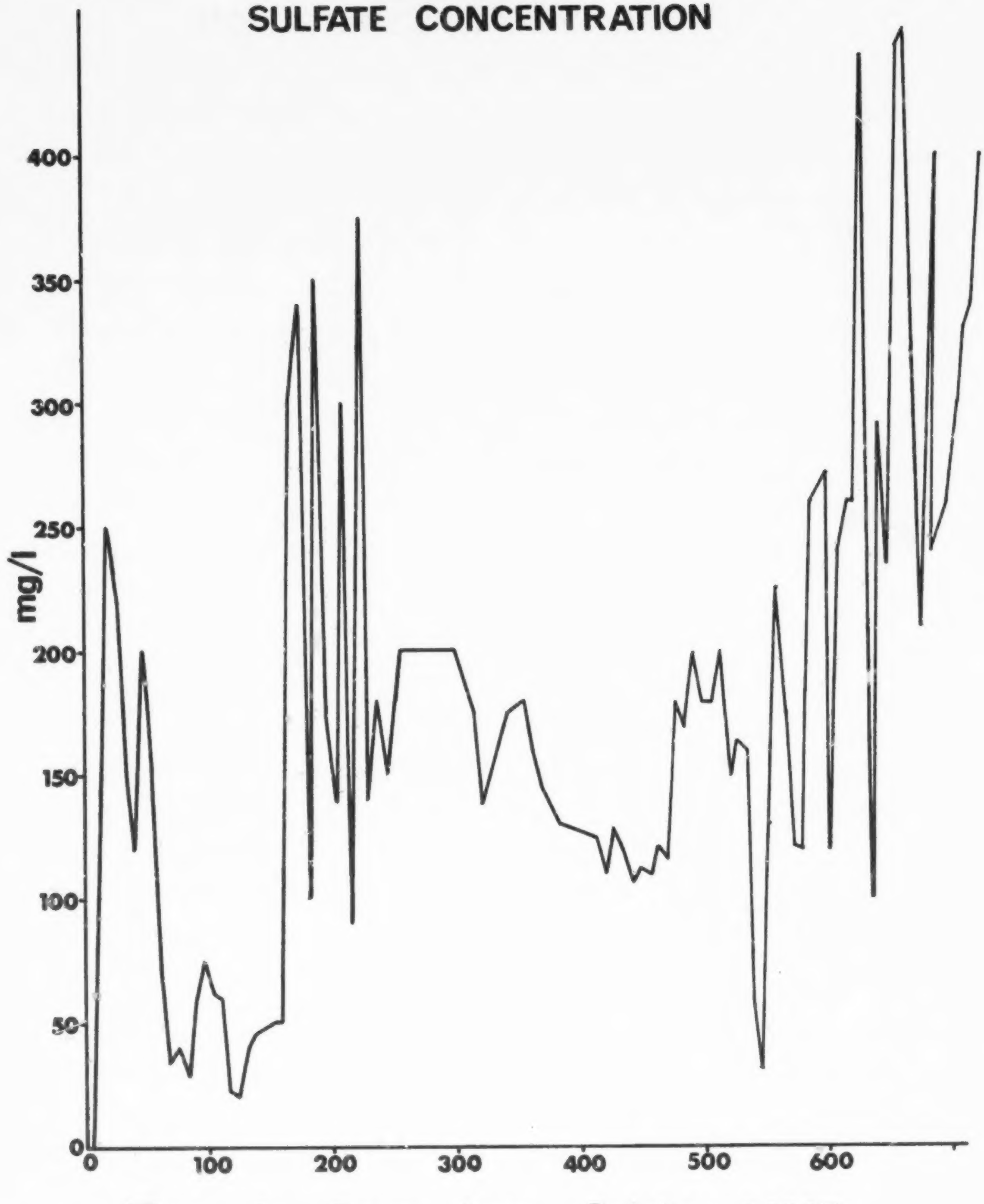


FIGURE 24

increased to peaks between 325 and 375 mg/l. During a second high period at 600 days, concentrations peaked between 400 and 500 mg/l.

In general, sulfate ion concentration levels increased with increased leachate production, and as the system approached field capacity. It appears as if periods of high sulfate ion concentration lag somewhat behind periods of high leachate production. Sulfate removed during the test totaled 300 grams with most obtained during the latter portion of the test period.

Chloride

The chloride ion concentration curve is presented in Figure 25. Initial chloride ion concentrations peaked at 700 mg/l shortly after test initiation. Concentrations decreased to relatively low levels during the period between 30 and 210 days and then increased to a maximum of almost 2400 mg/l. They then decreased to the 1700 mg/l concentration level where they remained for a sustained period. Toward the end of the test period they decreased to approximately 200 mg/l with a trend toward higher values at the end of the period.

As seen in Figure 38, approximately 300 grams of chloride were removed during the test period.

Sodium

Figure 26 is the sodium ion concentration curve. The general shape of this curve differs from any previously presented data. Sodium ion concentrations reached 3800 mg/l in the time period between 200 and 250 days. This peak occurred at the same time as the chloride ion. However, the sodium concentration curve does not have sustained concentration levels as the chloride concentration curve. After the initial peak, concentration

LYSIMETER
CHLORIDE CONCENTRATION

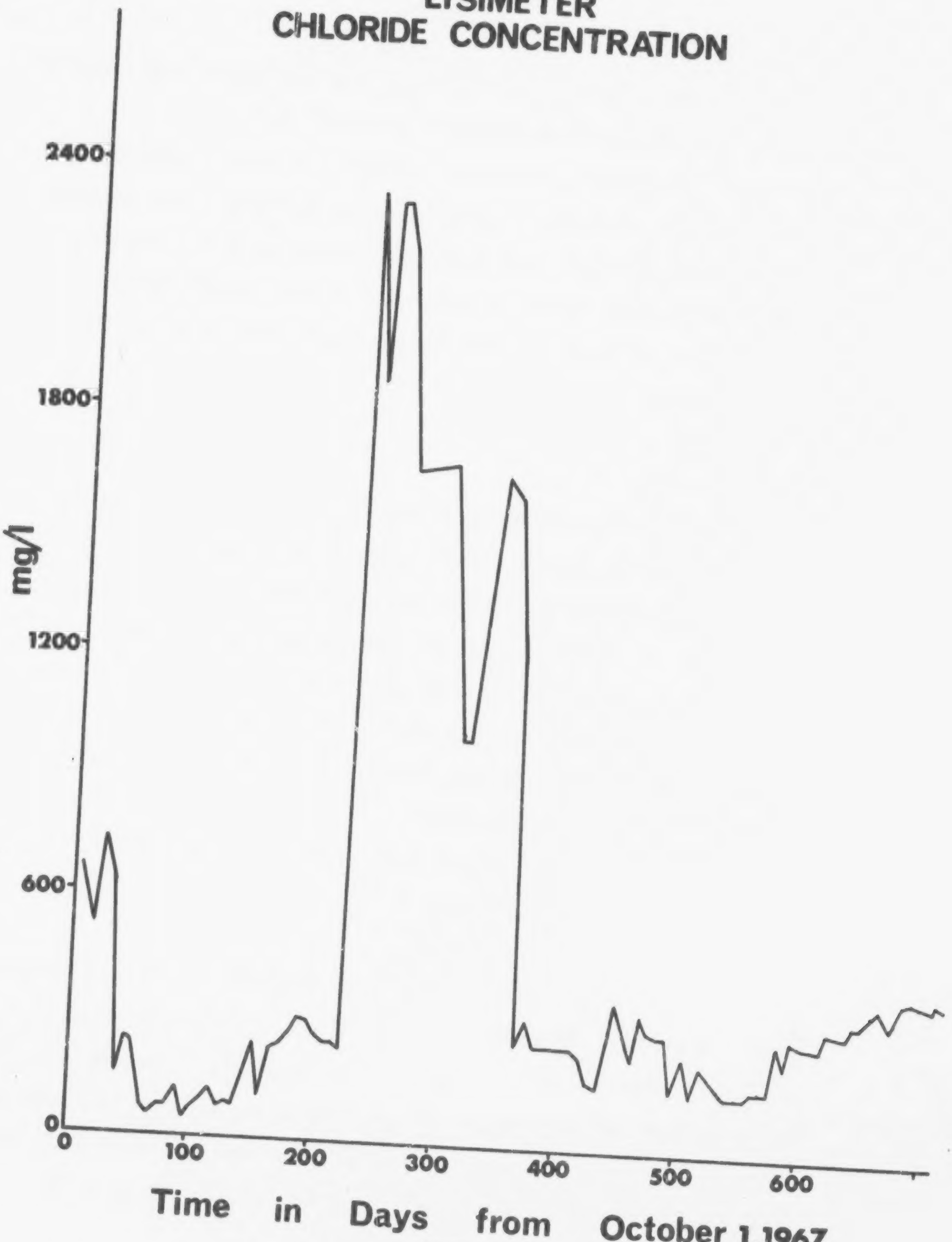


FIGURE 25

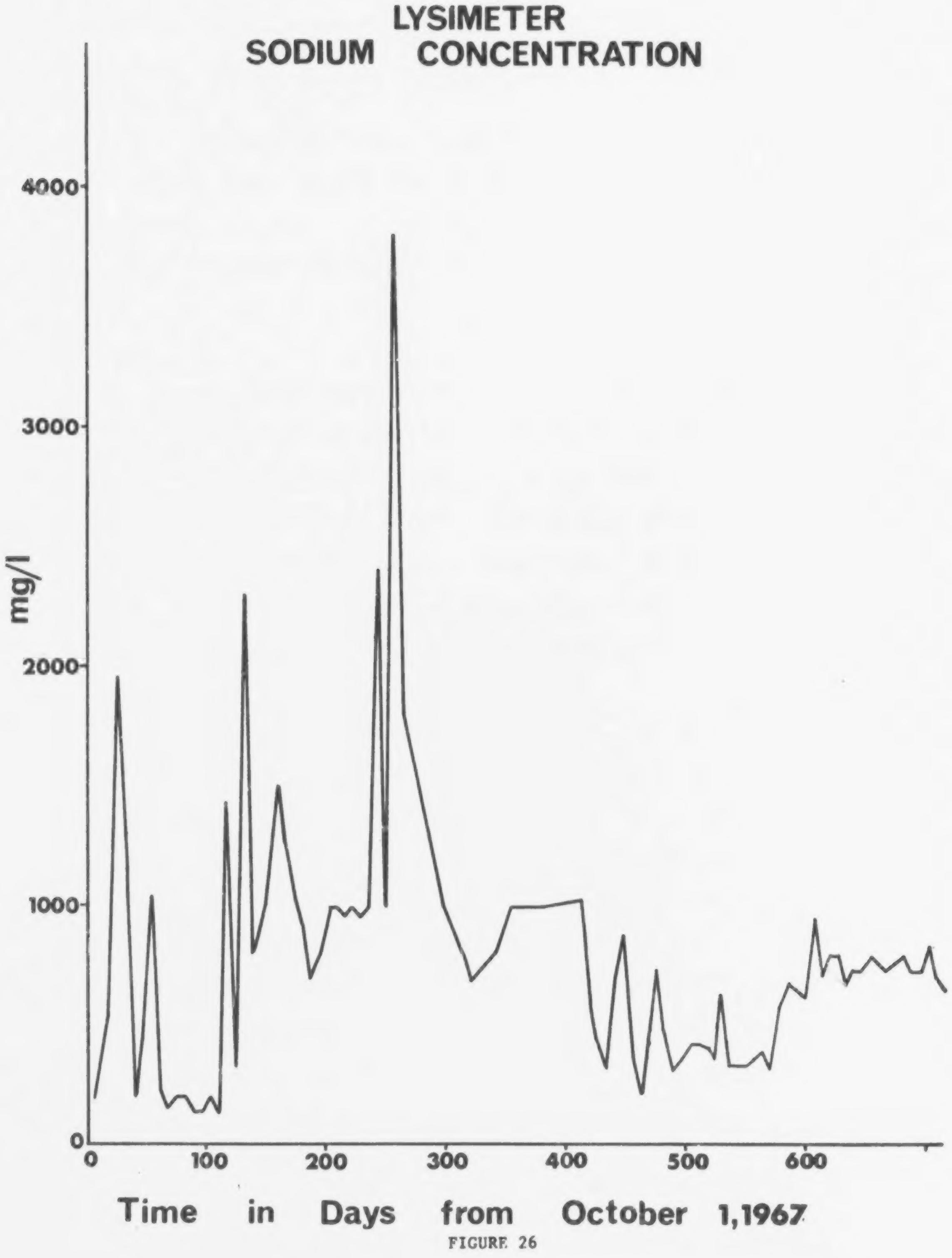

LYSIMETER
SODIUM CONCENTRATION
mg/l
4000
3000
2000
1000
0
0
100
200
300
400
500
600
Time in Days from October 1,1967

FIGURE 26

levels decreased to as low as 200 mg/l and then increased with a trend toward significantly higher values at the end of this period. This behavior pattern in similar to that of the chloride ion.

As seen in Figure 39, a total of 650 grams of sodium were removed during the test period.

Nitrogen

The curve for organic nitrogen concentration is presented in Figure 27. Organic nitrogen concentration decreased from an initial peak of 432 mg/l to a value of 8 mg/l at the end of three months. In general, this curve shows that organic nitrogen was increasing during the test period with localized peaks. In the latter portion of the test period, concentration levels ranged between 100 and 200 mg/l. It is believed that the initial peak was due to squeezing of the organic materials during the compaction process.

A curve for total nitrogen (organic) removed is presented in Figure 40. The total removed was 125 grams. A curve for free nitrogen is presented in Figure 41. The total removed was approximately 90 grams.

Hardness (as $CaCO_3$)

The hardness concentration curve is shown in Figure 28. Except for two periods, hardness concentration levels exceeded 1500 mg/l and at 420 days peaked at 5500 mg/l. Most frequent values ranged between 2250 and 2750 mg/l. As indicated in the total hardness curve, Figure 42, approximately 2800 grams were removed during the test period.

LYSIMETER ORGANIC NITROGEN CONCENTRATION

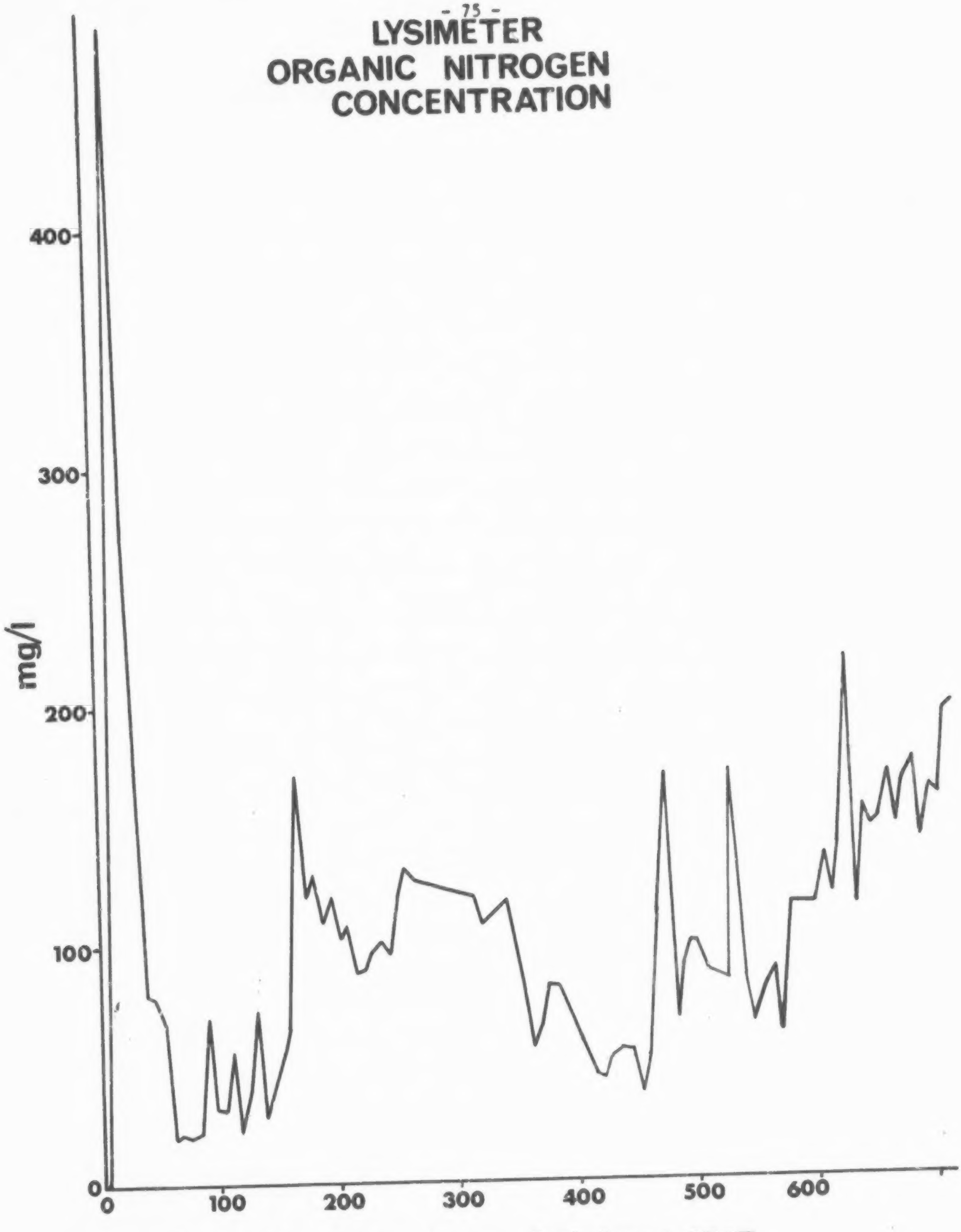


FIGURE 27

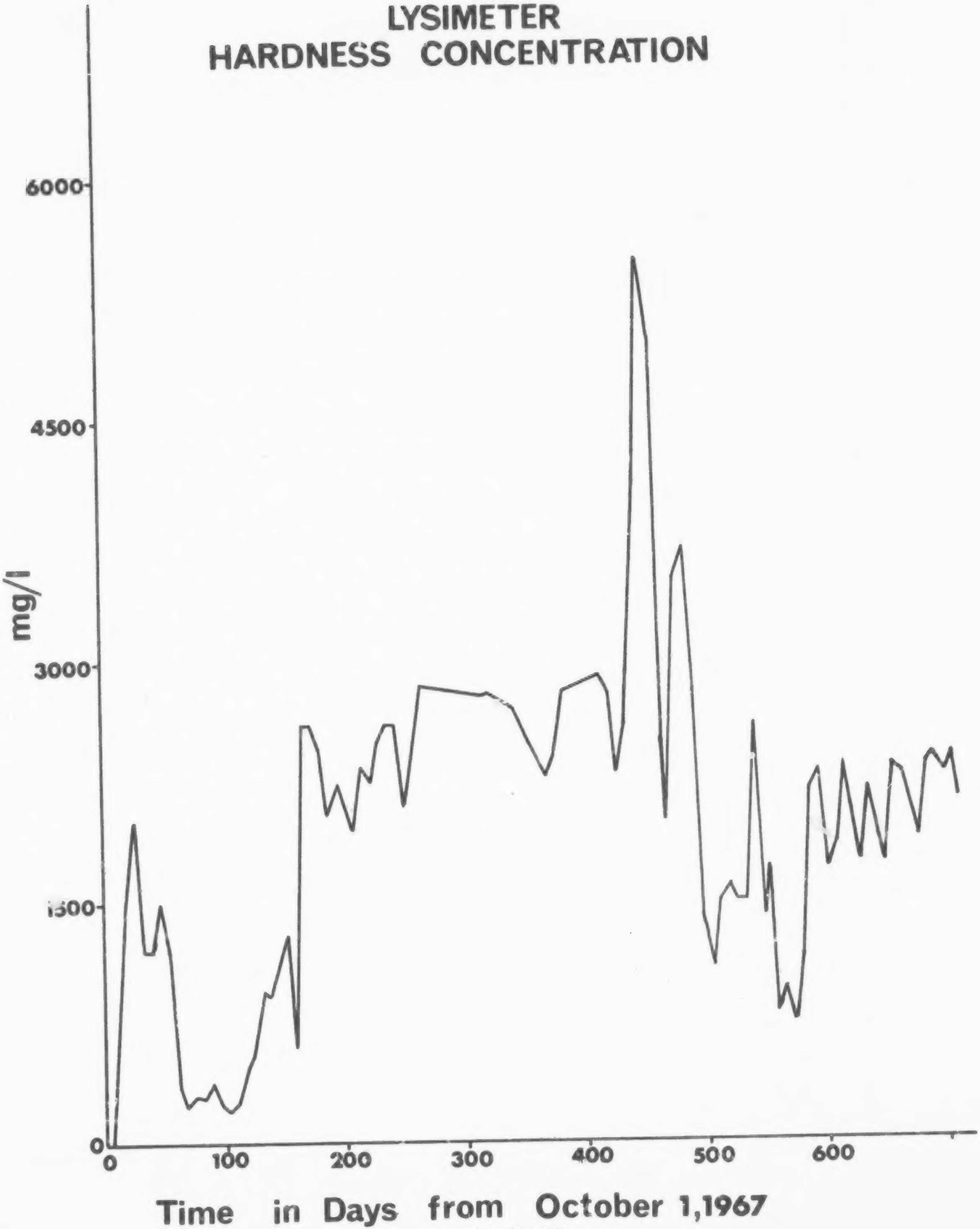

LYSIMETER
HARDNESS CONCENTRATION
mg/l
6000
4500
3000
1500
0
0
100
200
300
400
500
600
Time in Days from October 1,1967

FIGURE 28

Chemical Oxygen Demand

Figure 29 shows that chemical oxygen demand concentrations were in excess of 50,000 mg/l within one month of the initiation of the test. It is believed that this initial peak was caused by the release of some of the organic components due to the compaction and placement process. After the initial peak, chemical oxygen demand decreased to a minimum of 1,000 mg/l after 120 days. Thereafter, it increased with localized peaks and valleys. Most frequent concentration levels fell between 20,000 and 22,000 mg/l.

As indicated in Figure 43, chemical oxygen demand during the test period totaled approximately 17,000 grams.

Suspended and Total Solids

The curve for suspended solids concentrations is presented in Figure 30, and the curve of total solids concentration is presented in Figure 31. In general, concentration levels were random with no readily discernible pattern. Initial values for suspended solids were 26,500 mg/l and for total solids, they were in excess of 40,000 mg/l.

As indicated in Figure 44, approximately 700 grams of suspended solids were removed by the leachate during the test period.

Nickel

The nickel ion concentration curve is presented in Figure 32. No nickel was detected prior to 150 days of elapsed test time. After that time, nickel was present in concentrations with peaks at 0.8 mg/l at 300 days, and 0.9 mg/l at 710 days. The most frequent concentration levels fell between 0.2 and 0.3 mg/l. During the test period, less than 0.2 grams of nickel were removed (Fig. 45).

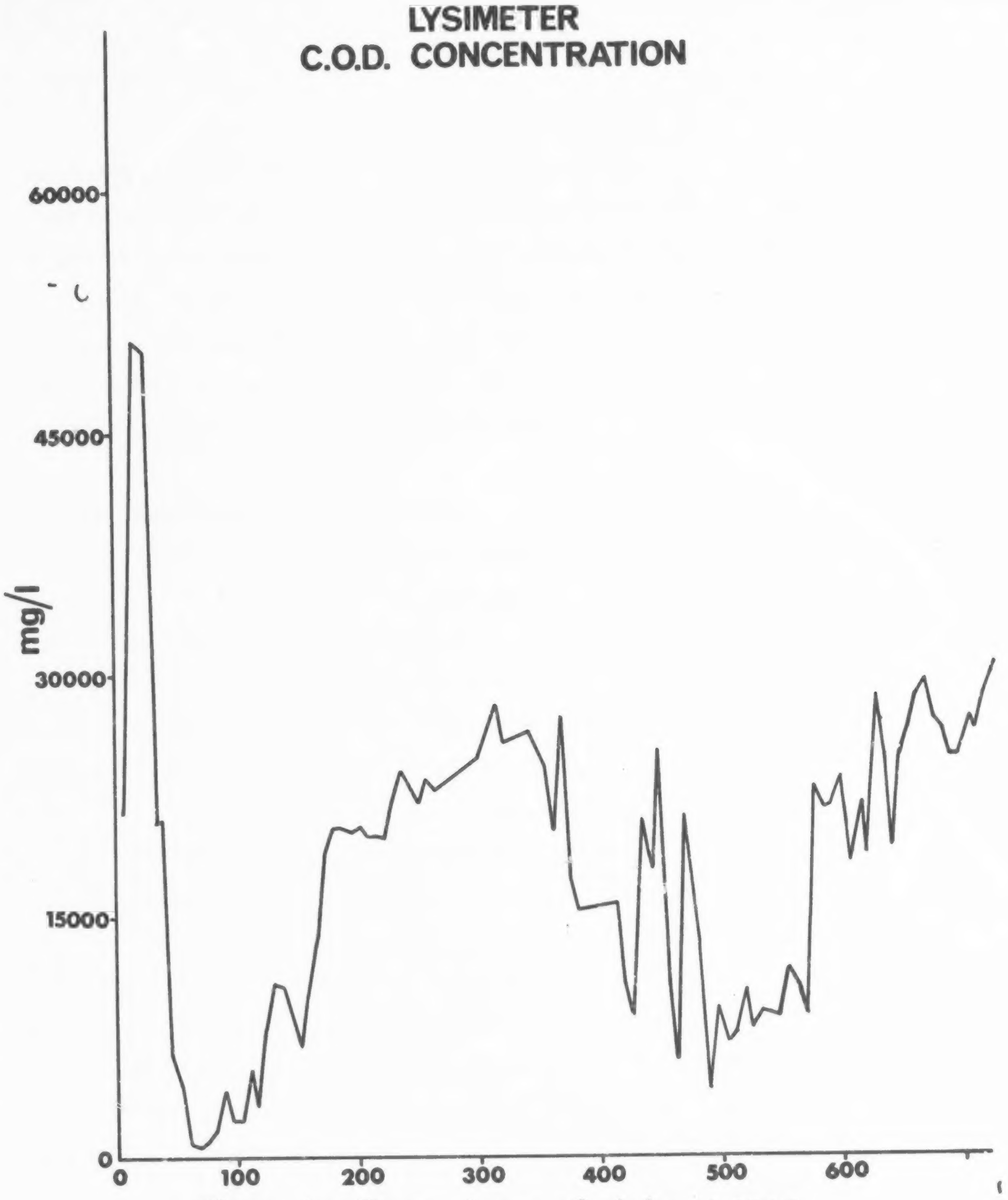

LYSIMETER
C.O.D. CONCENTRATION
60000
45000
30000
15000
0
mg/l
0
100
200
300
400
500
600
Time in Days from October 1,1967

FIGURE 29

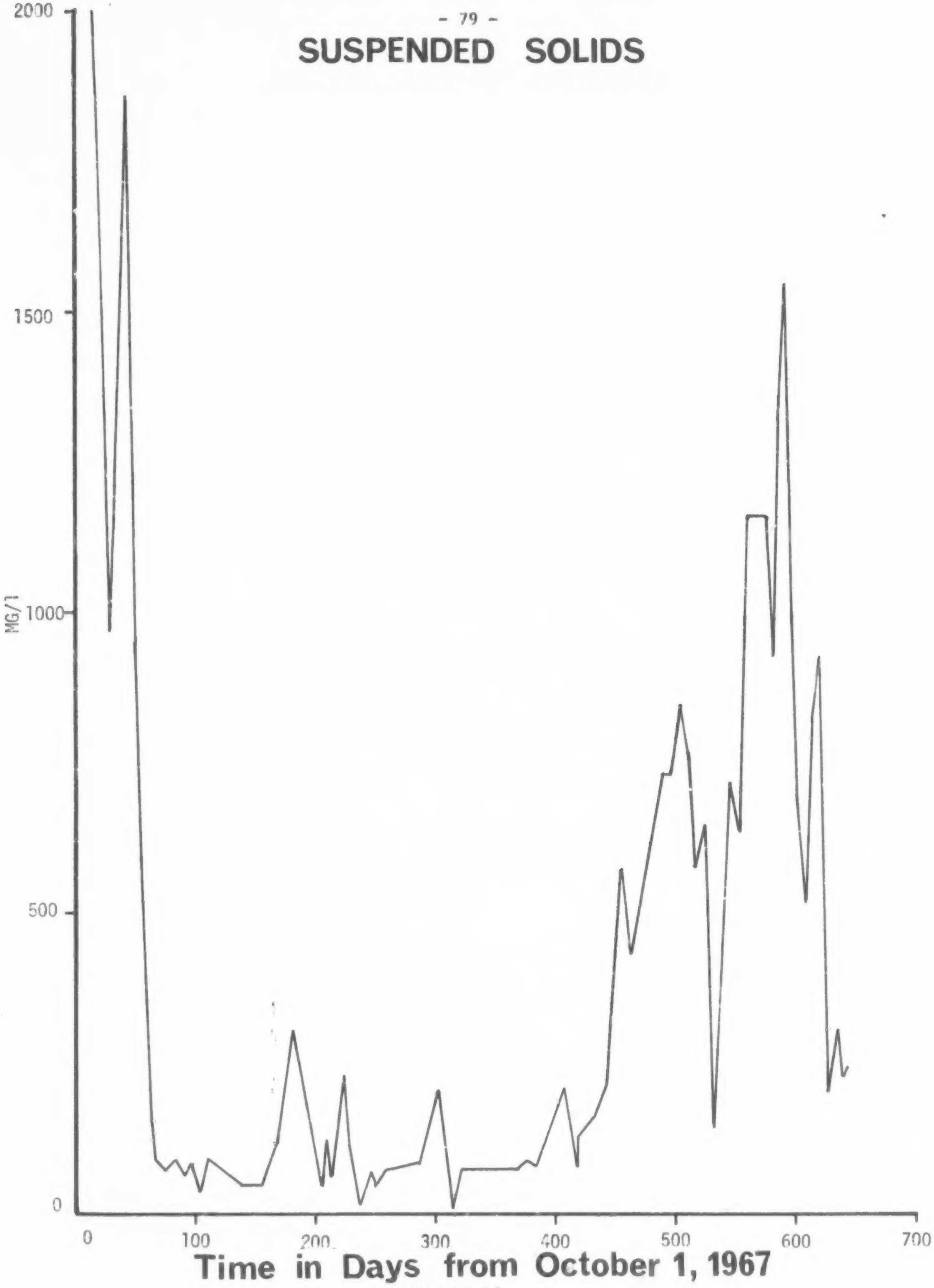

SUSPENDED SOLIDS
MG/1
2000
1500
1000
500
0
0
100
200
300
400
500
600
700
Time in Days from October 1, 1967

FIGURE 30

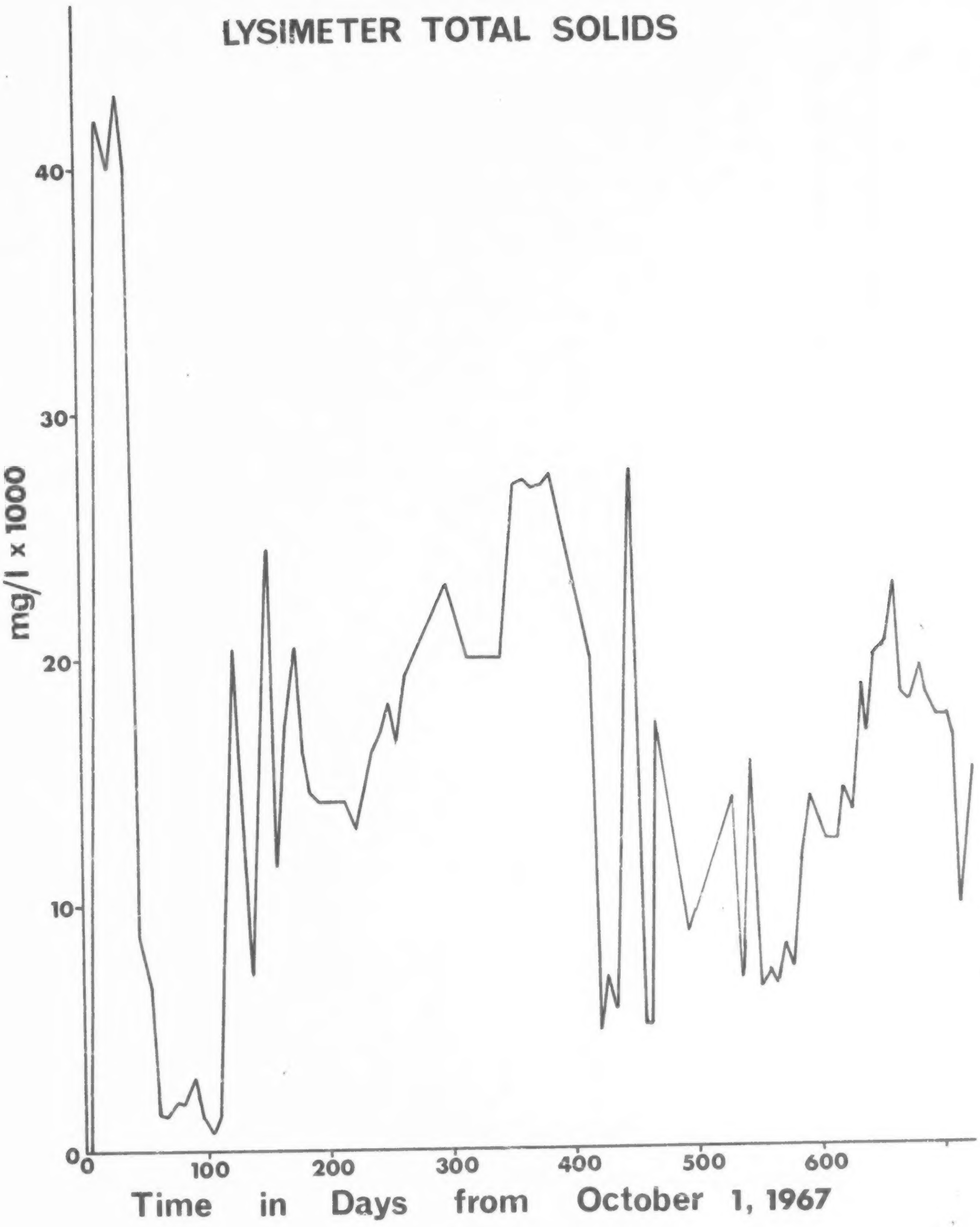

LYSIMETER TOTAL SOLIDS
mg/l x 1000
40
30
20
10
0
0
100
200
300
400
500
600
Time in Days from October 1, 1967

FIGURE 31

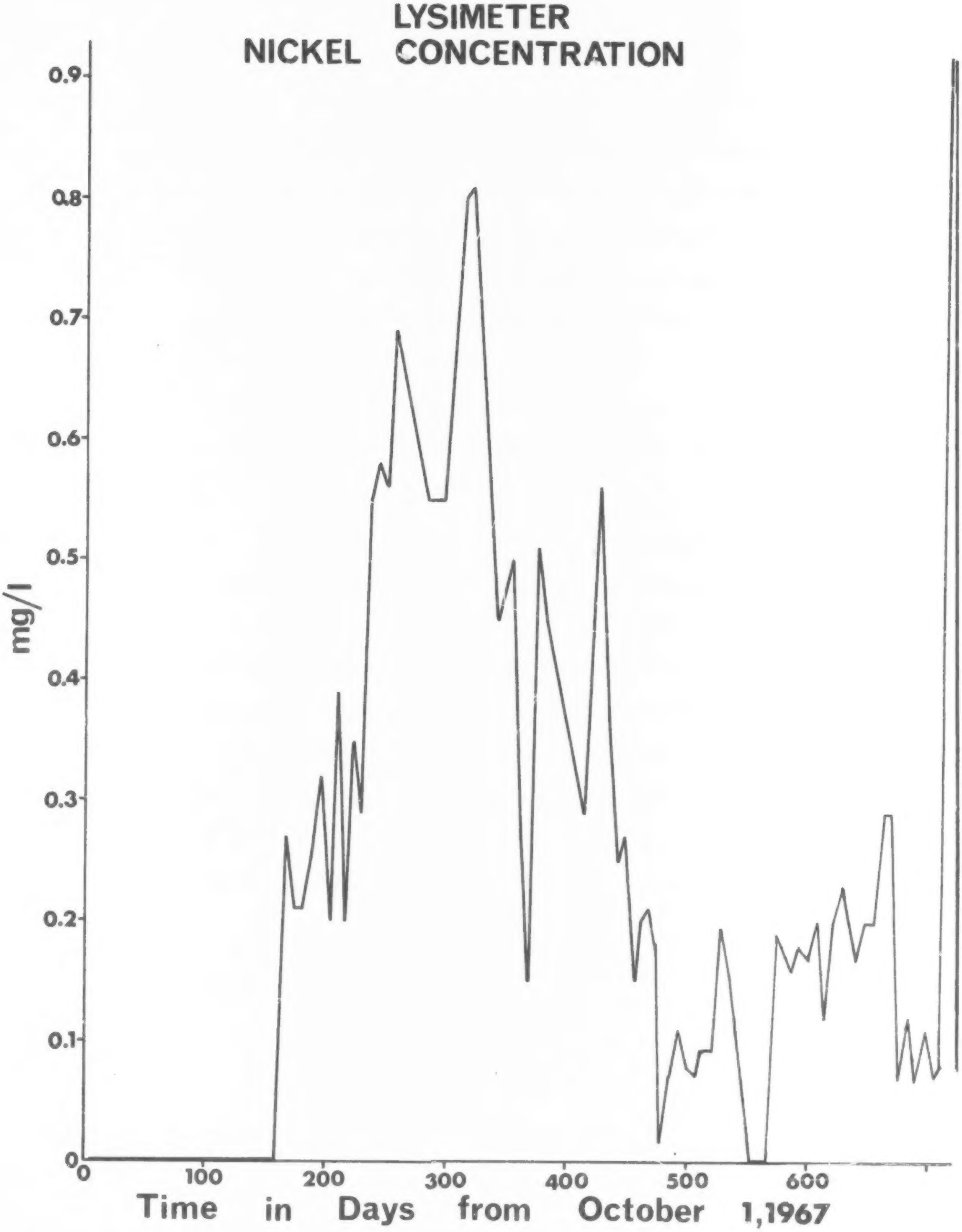

LYSIMETER
NICKEL CONCENTRATION
mg/l
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
100
200
300
400
500
600
Time in Days from October 1,1967

FIGURE 32

Copper

The copper ion concentration curve is presented in Figure 33. A peak of 4.7 mg/l occurred at 150 days and a peak of 7.6 mg/l occurred at 590 days. Concentration levels were less than one mg/l except for the latter part of the test period when they increased slightly. The copper ion concentration pattern appears to be independent of any of the other parameters measured.

As indicated in Figure 46, less than one gram of copper was removed during the test period and most removal occurred at the end of the period.

Lysimeter Temperatures

Curves for temperatures at various locations within the lysimeter are presented in Figure 47. The dotted curve (number 3) represents the average monthly air temperatures, as listed in Table 1. The general pattern of initial temperature behavior can be described as a rapid increase in the temperature at the refuse center followed by a slower rate of increase at adjacent levels. The center temperature peaked at 154^{o}F, whereas, temperatures at adjacent levels did not exceed 143^{o}F, and generally were not in excess of 110^{o}F to 115^{o}F. The temperature distri-

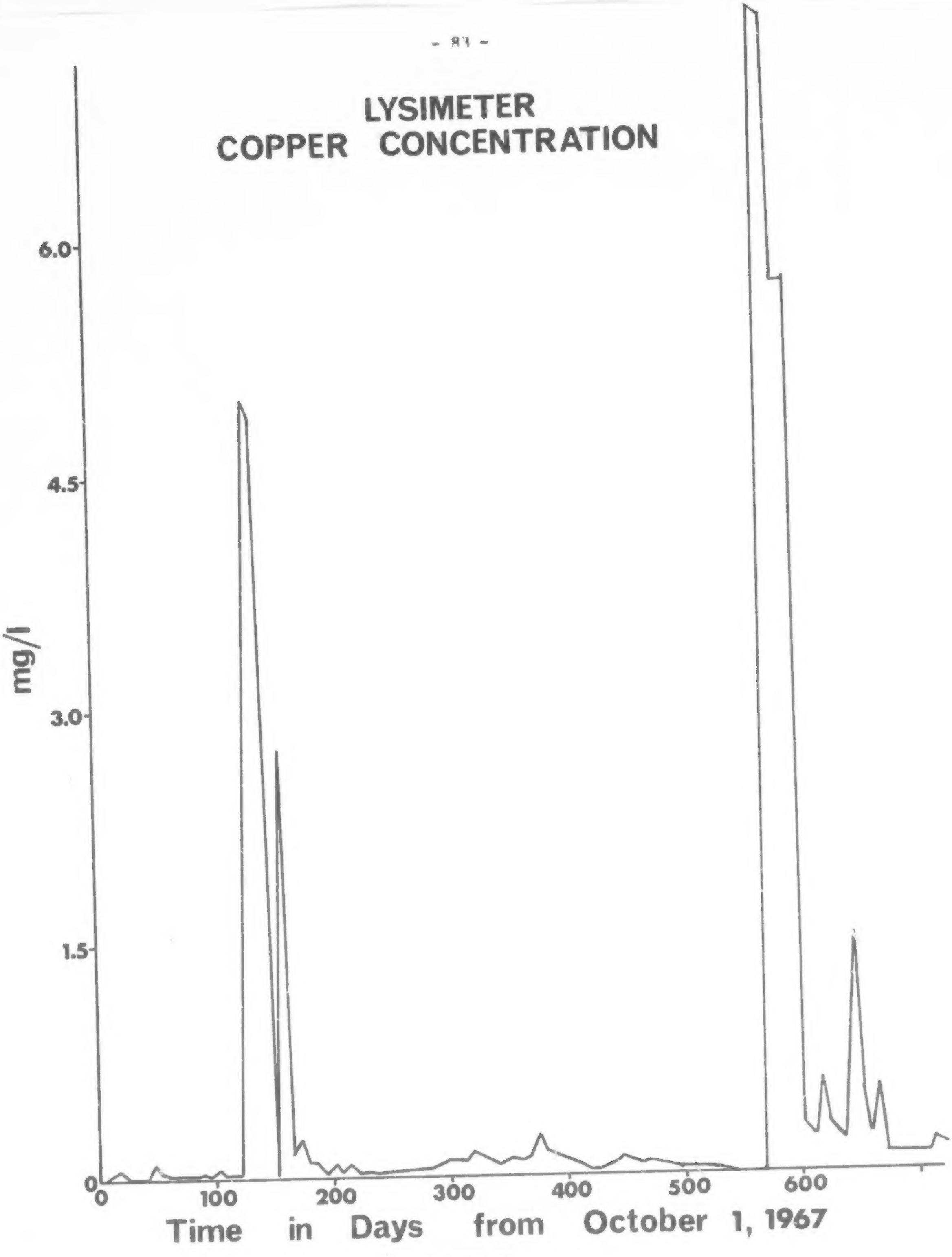
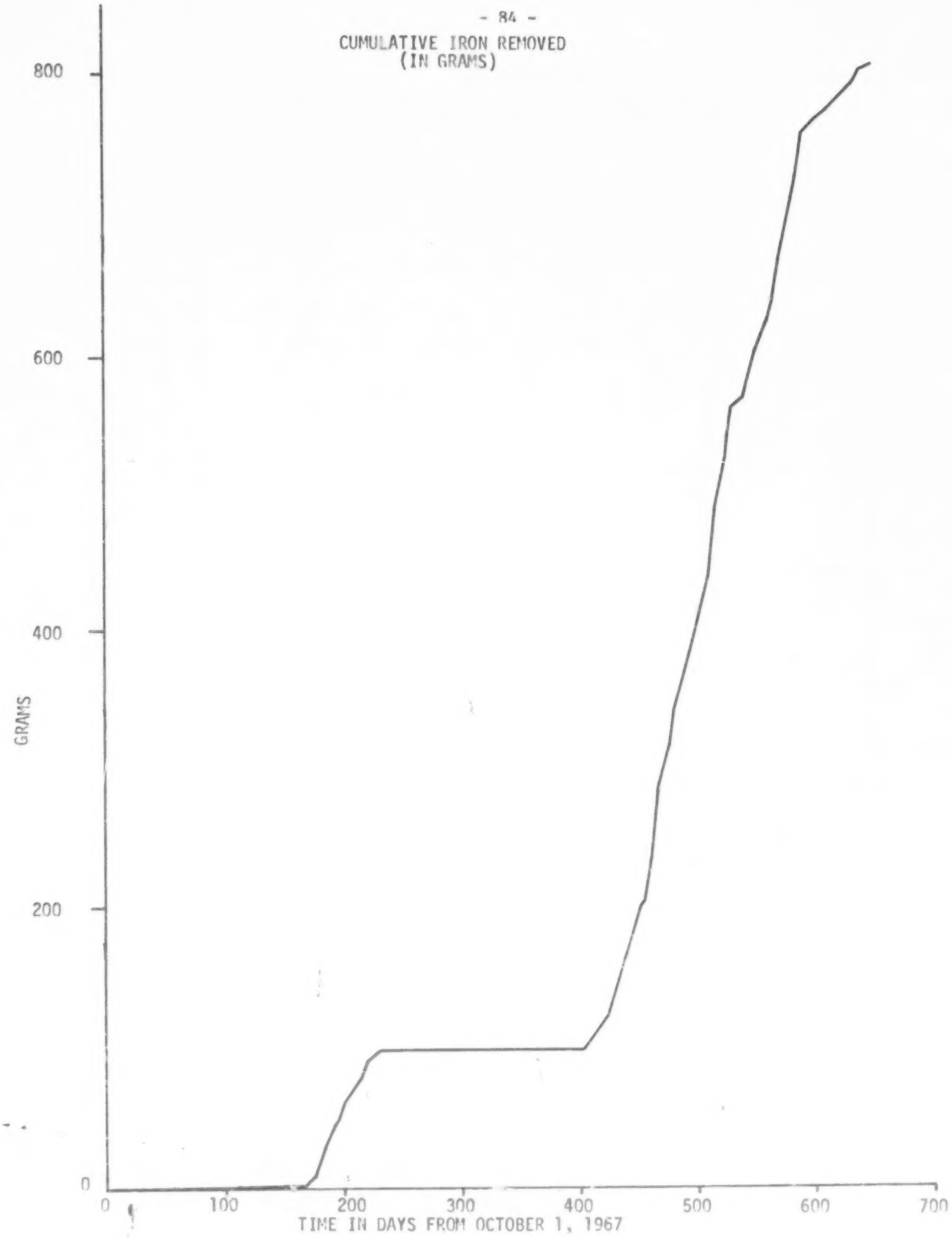

LYSIMETER
COPPER CONCENTRATION
mg/l
6.0
4.5
3.0
1.5
0
0
100
200
300
400
500
600
Time in Days from October 1, 1967

FIGURE 33



CUMULATIVE IRON REMOVED
(IN GRAMS)

FIGURE 34

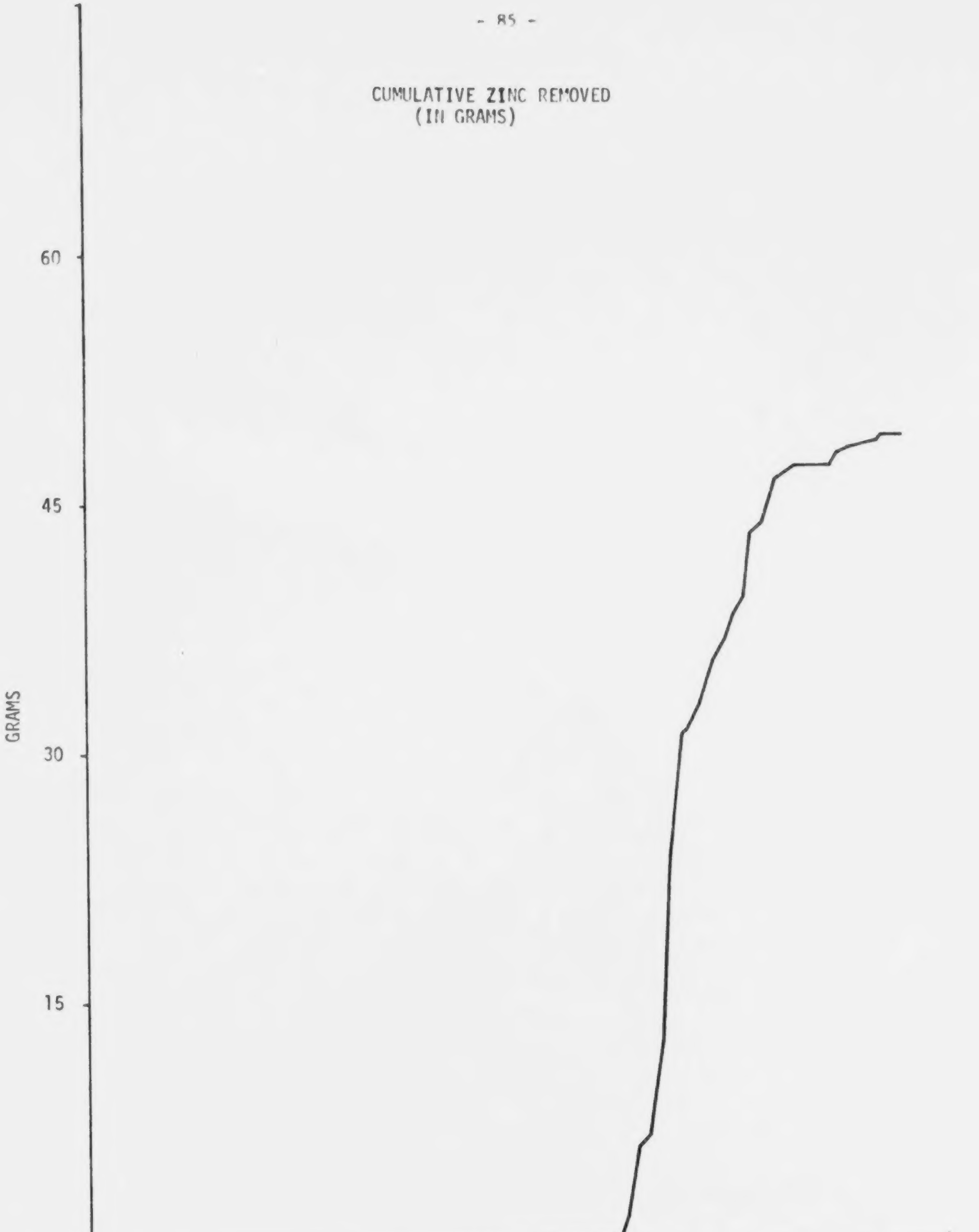

CUMULATIVE ZINC REMOVED
(IN GRAMS)
GRAMS
60
45
30
15
0
0
100
200
300
400
500
600
700
TIME IN DAYS FROM OCTOBER 1, 1967

FIGURE 35

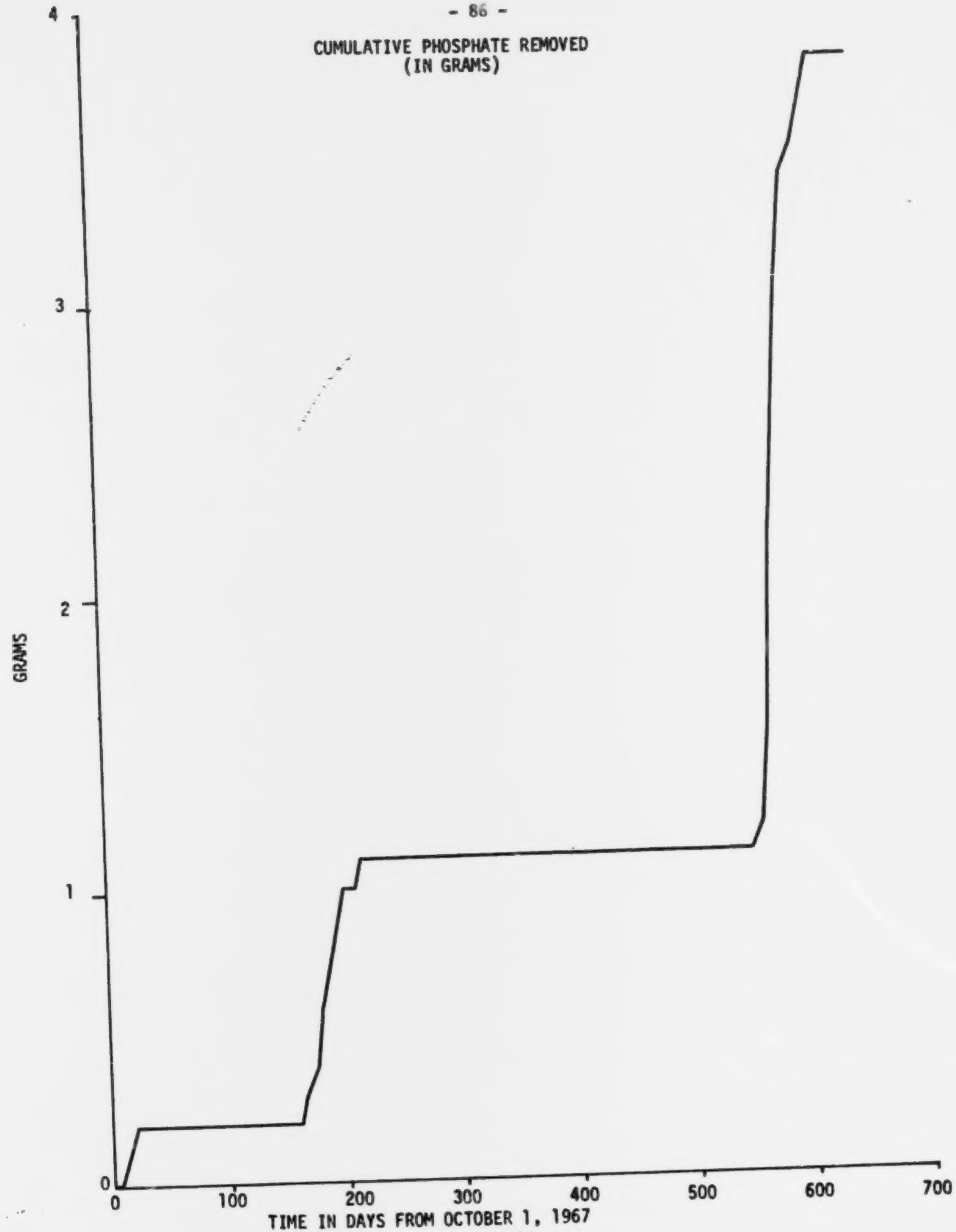

CUMULATIVE PHOSPHATE REMOVED
(IN GRAMS)
GRAMS
0
1
2
3
4
0
100
200
300
400
500
600
700
TIME IN DAYS FROM OCTOBER 1, 1967

FIGURE 36

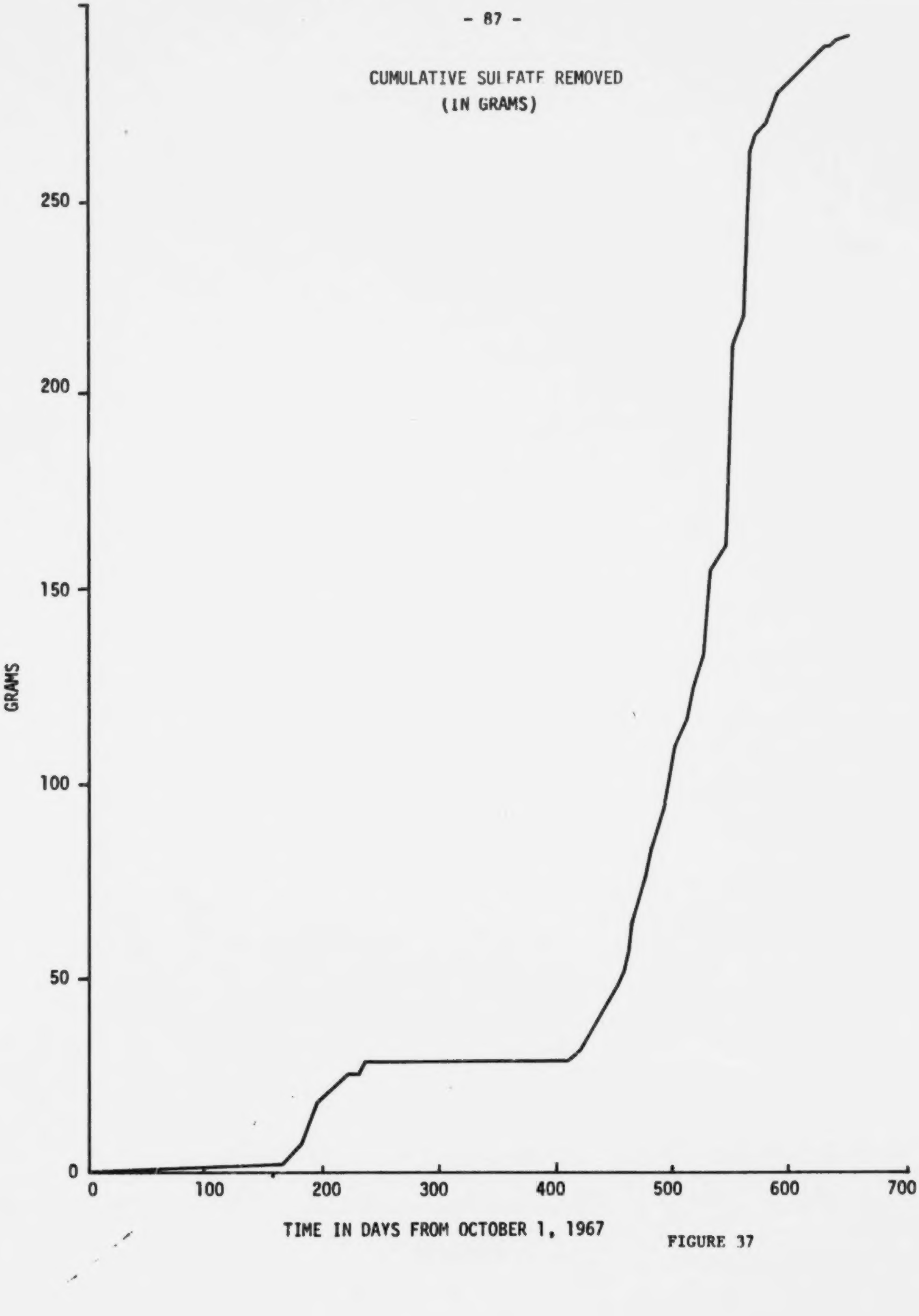

CUMULATIVE SULFATE REMOVED
(IN GRAMS)
GRAMS
0
50
100
150
200
250
0
100
200
300
400
500
600
700
TIME IN DAYS FROM OCTOBER 1, 1967

FIGURE 37

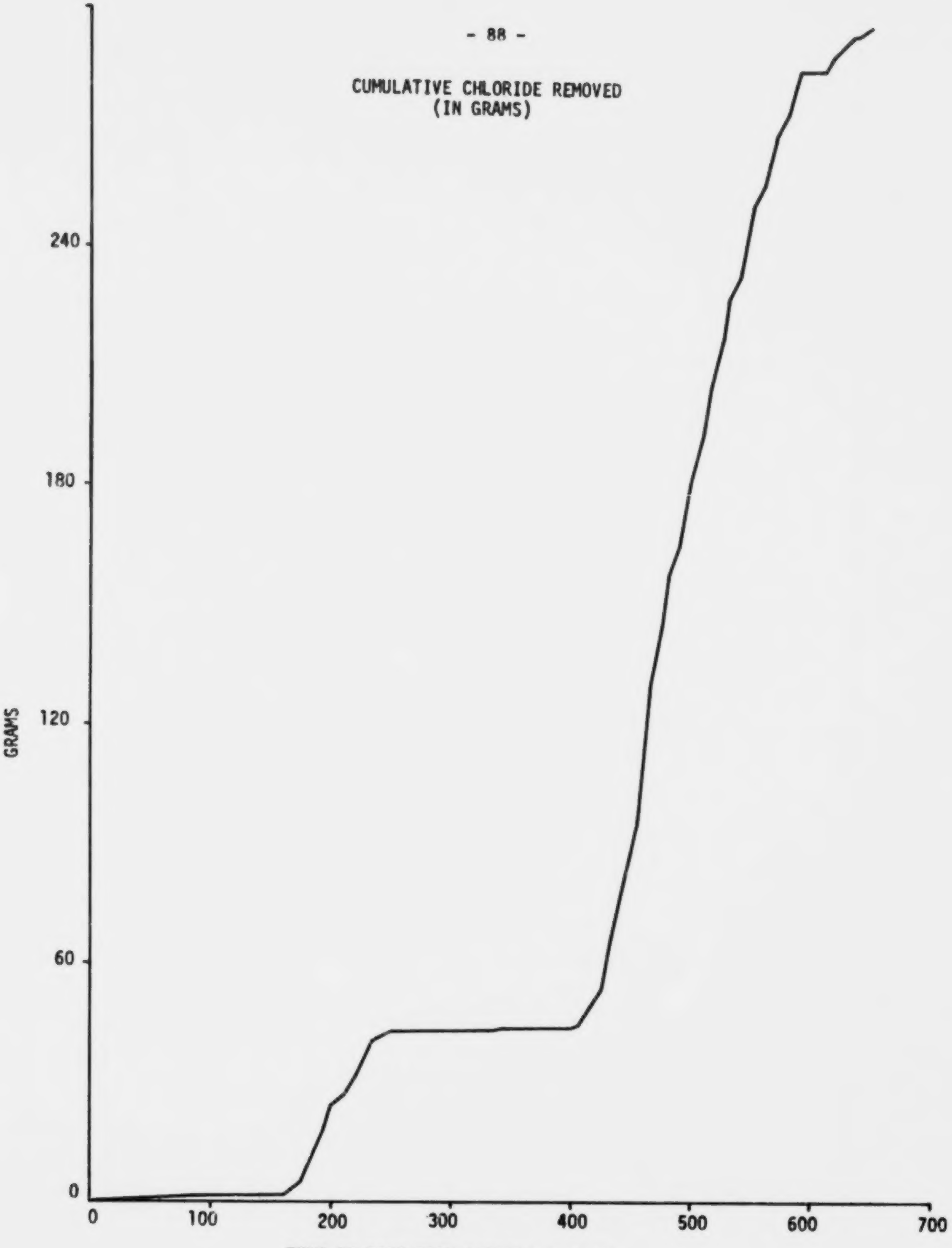

CUMULATIVE CHLORIDE REMOVED
(IN GRAMS)
GRAMS
240
180
120
60
0
0
100
200
300
400
500
600
700
TIME IN DAYS FROM OCTOBER 1, 1967

FIGURE 38

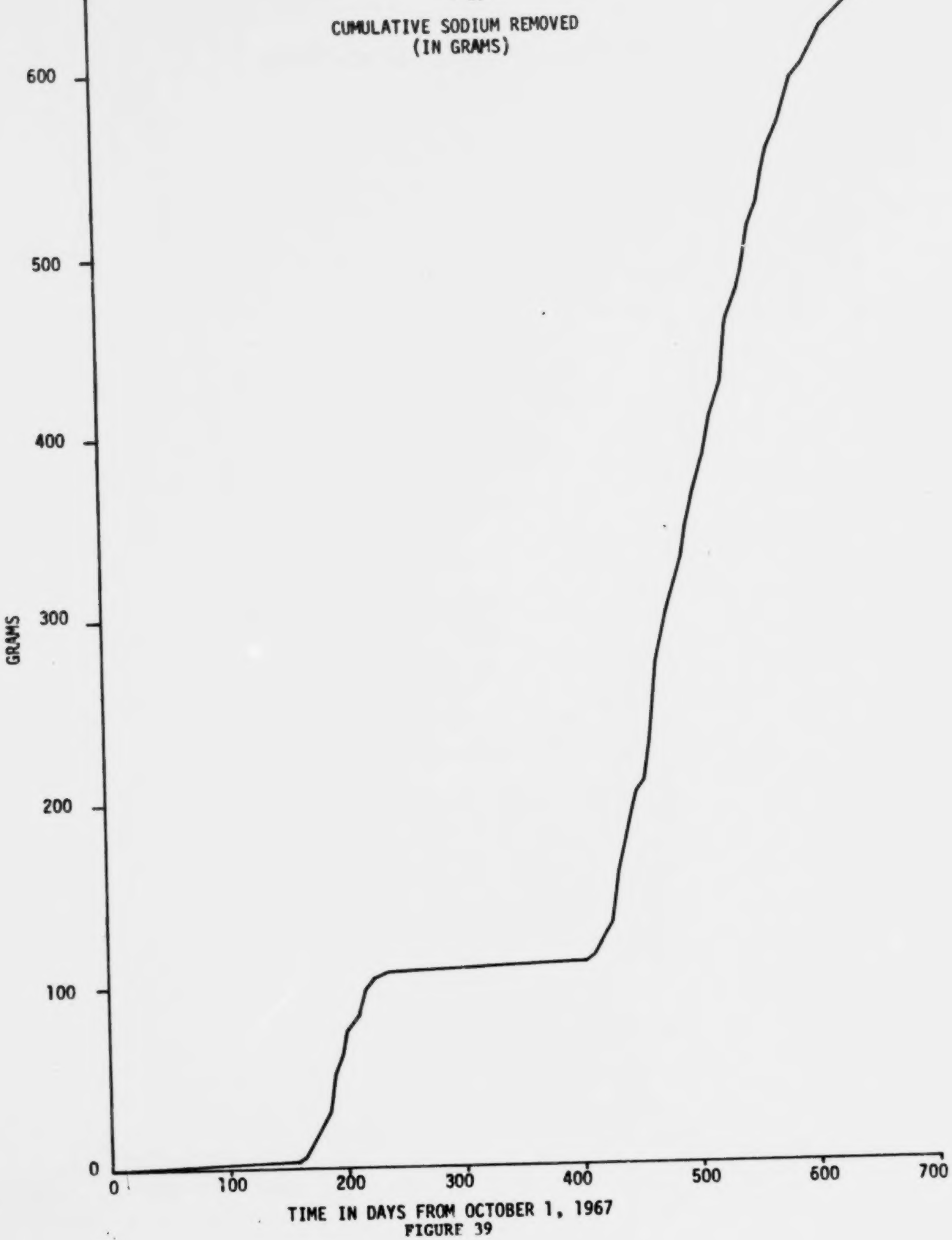

CUMULATIVE SODIUM REMOVED
(IN GRAMS)
GRAMS
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
TIME IN DAYS FROM OCTOBER 1, 1967

FIGURE 39

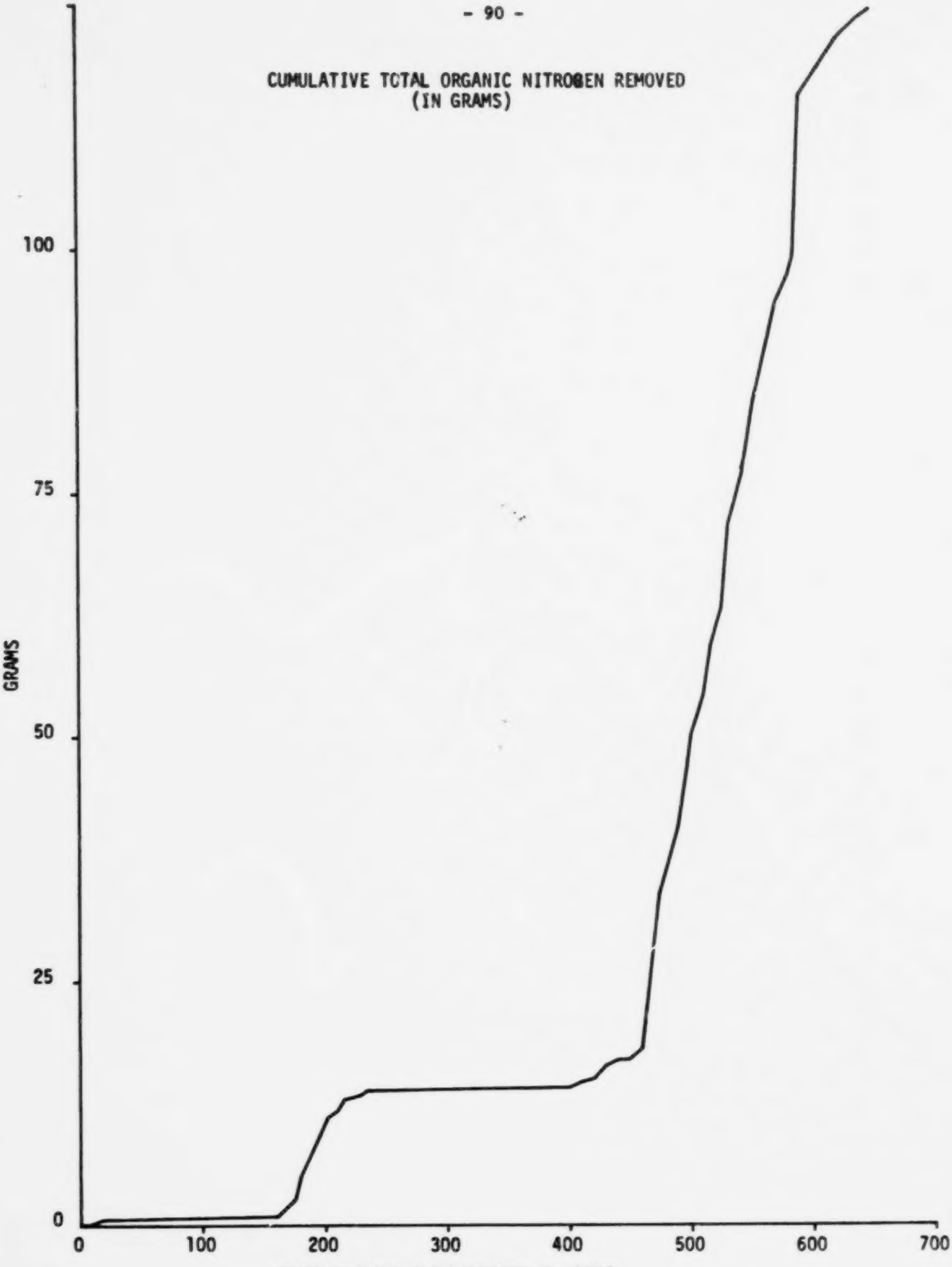

CUMULATIVE TOTAL ORGANIC NITROGEN REMOVED
(IN GRAMS)
GRAMS
100
75
50
25
0
0
100
200
300
400
500
600
700
TIME IN DAYS FROM OCTOBER 1, 1967

FIGURE 40

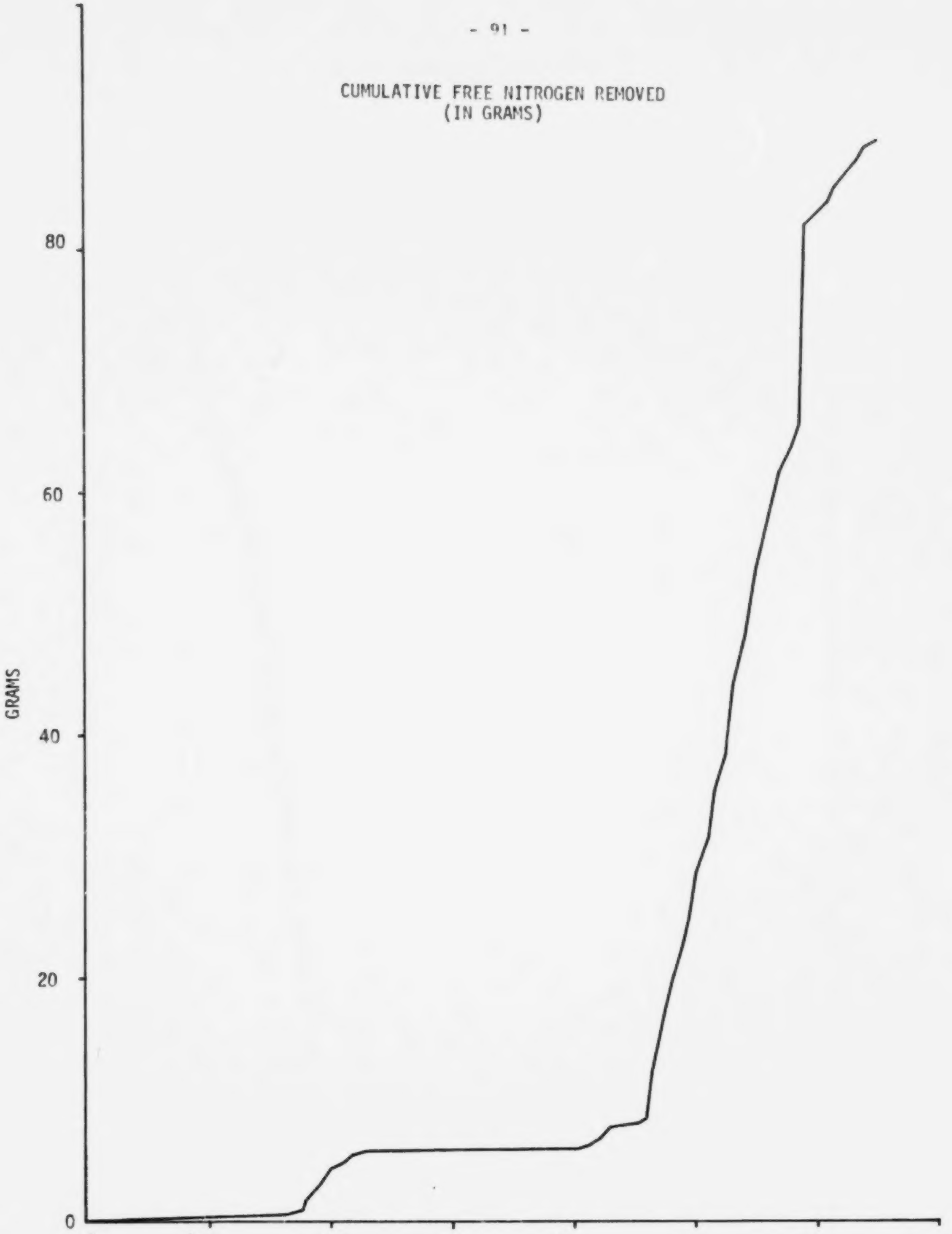

CUMULATIVE FREE NITROGEN REMOVED
(IN GRAMS)
GRAMS
0
20
40
60
80
0
100
200
300
400
500
600
700
TIME IN DAYS FROM OCTOBER 1, 1967

FIGURE 41

CUMULATIVE HARDNESS REMOVED
(IN GRAMS)

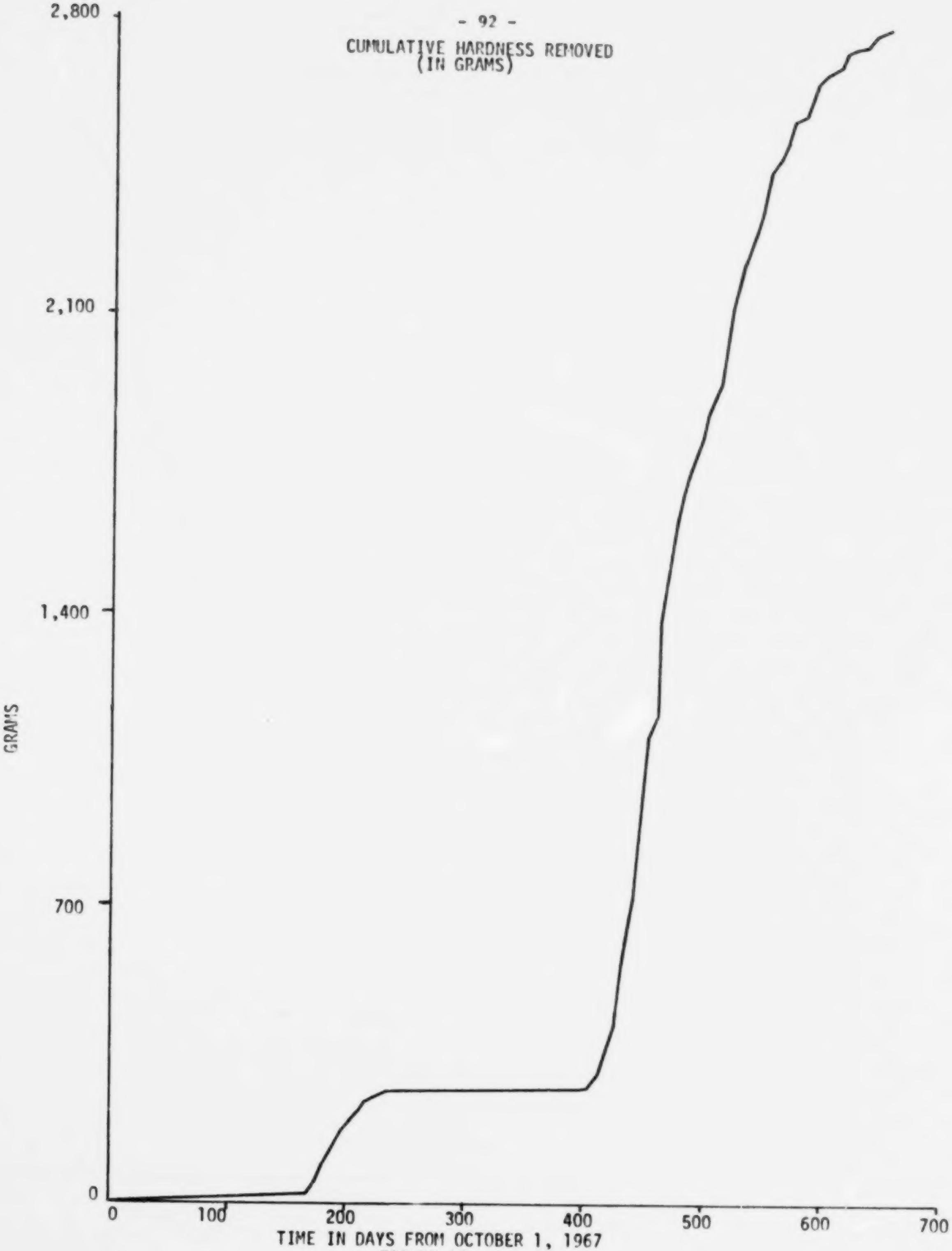


FIGURE 42

CUMULATIVE COD REMOVED
(IN GRAMS)

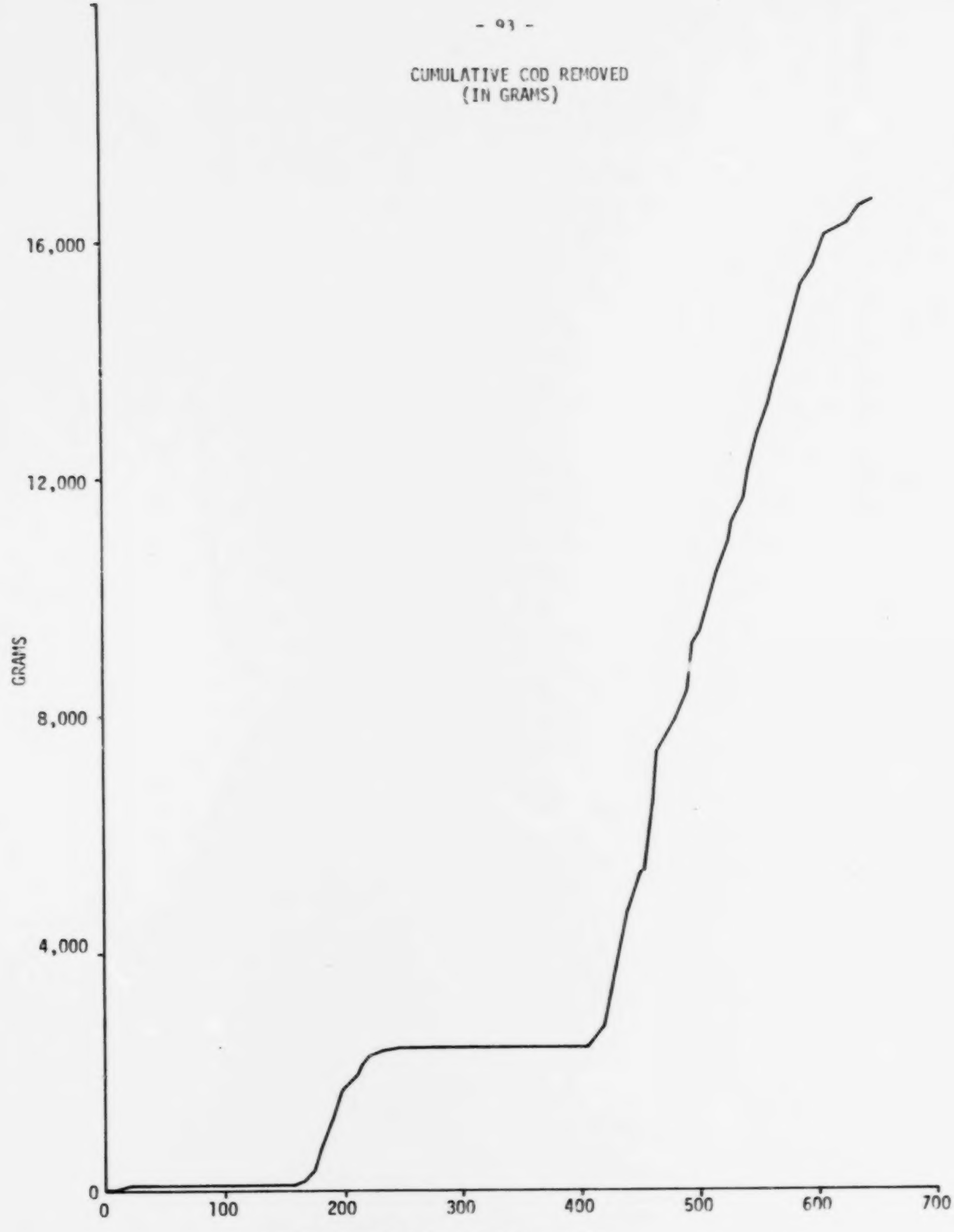


FIGURE 43

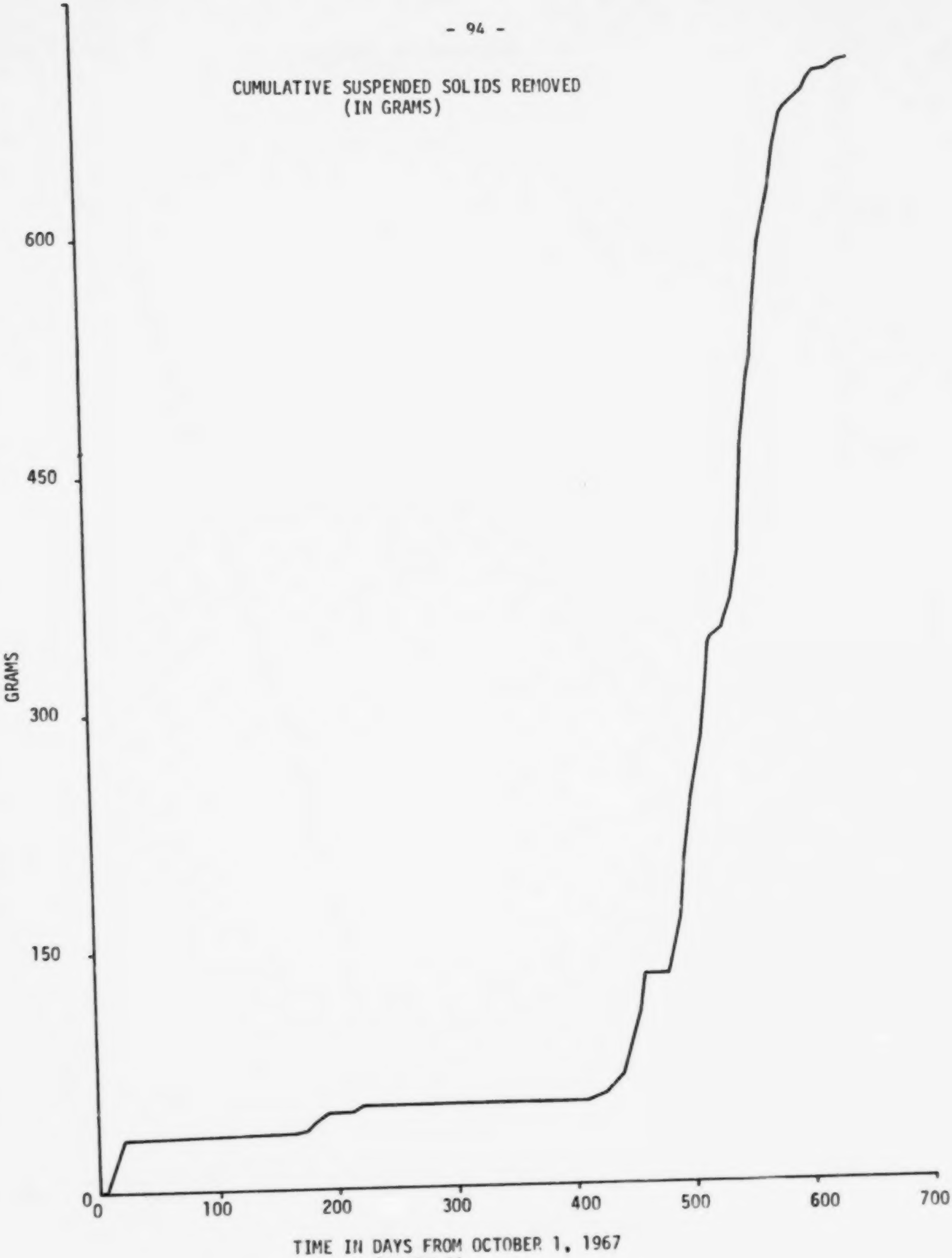

CUMULATIVE SUSPENDED SOLIDS REMOVED
(IN GRAMS)
GRAMS
600
450
300
150
0
0
100
200
300
400
500
600
700
TIME IN DAYS FROM OCTOBER 1, 1967

FIGURE 44

CUMULATIVE NICKEL REMOVED
(IN GRAMS)

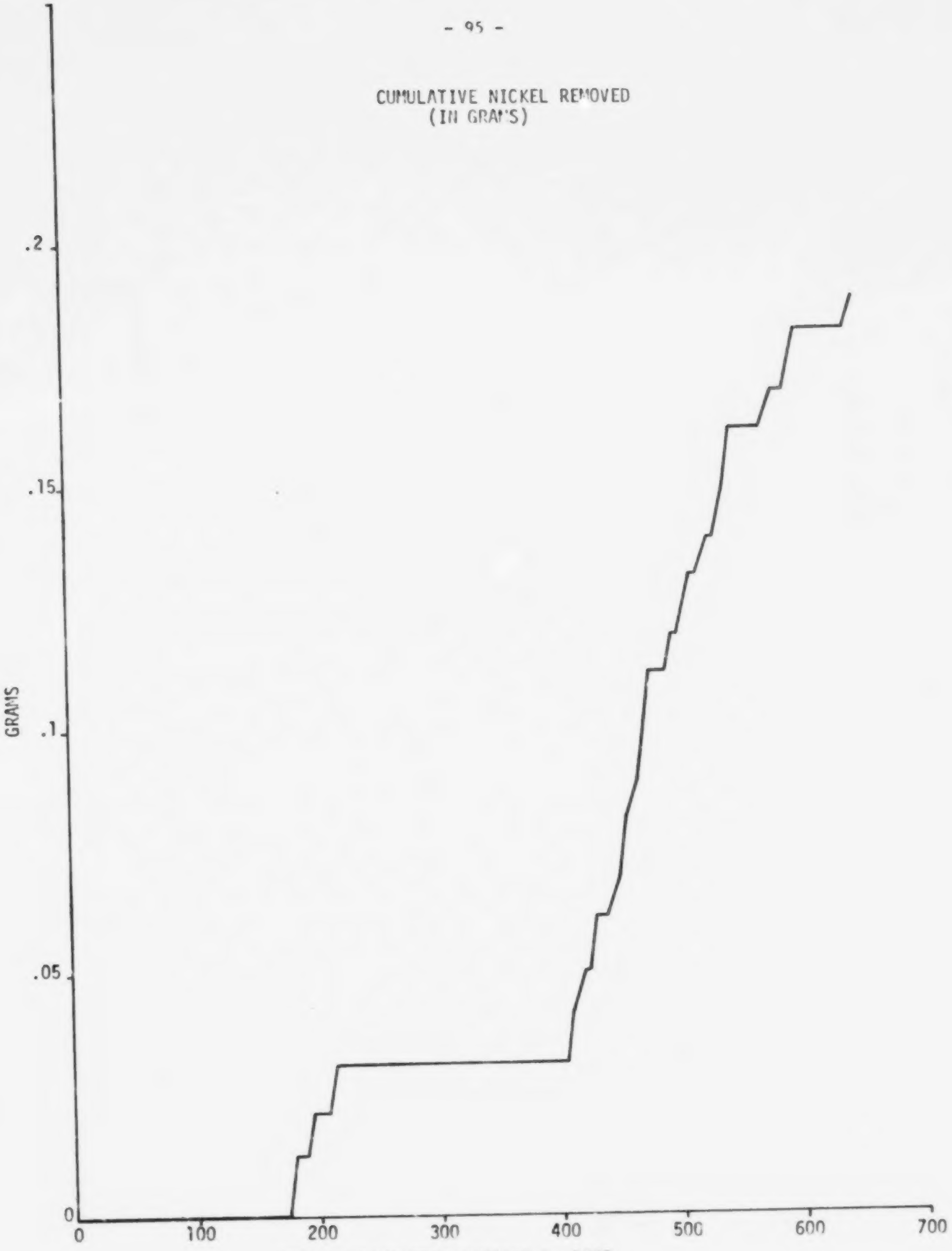


FIGURE 45

CUMULATIVE COPPER REMOVED
(IN GRAMS)

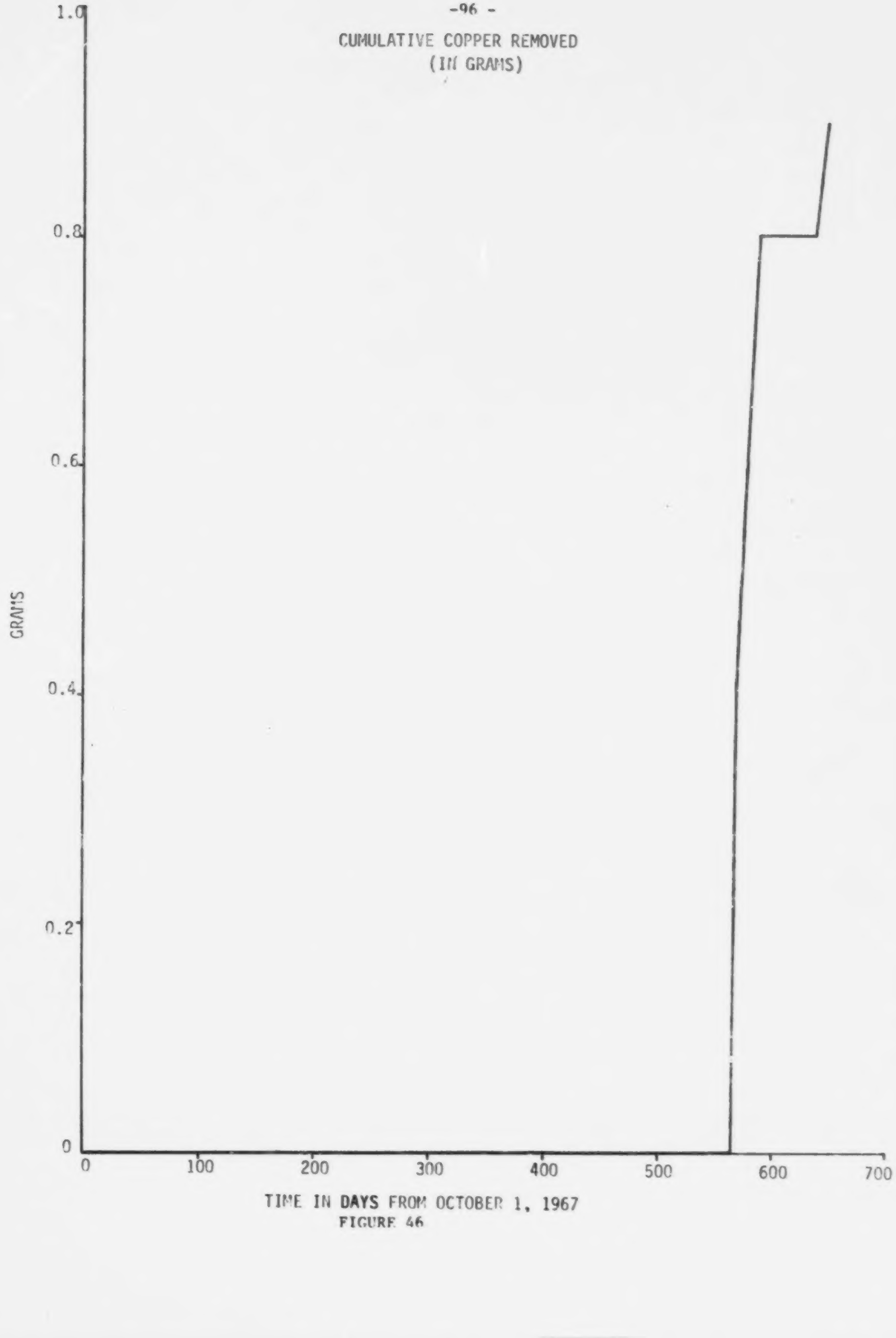


FIGURE 46

bution pattern indicates that temperatures in the layers of refuse adjacent to the center layer initially increased due to a spreading effect as heat flowed to both the top and bottom temperature controlled boundaries. The initial temperature distribution appeared to be controlled by conditions at the refuse center. Once adjacent levels reached their temperature peaks (after approximately 60 days), all temperatures showed a continuous gradual decline until virtually steady state temperatures prevailed.

The rapid temperature increase at the refuse center to a peak of 154^{o}F is of particular interest in that the rise occurred within 20 days of test initiation. Temperatures then slowly decreased until a 60 day time period had elapsed, and, thereafter, rapidly decreased to a temperature of approximately 80^{o}F. The initial increase in temperatures at the refuse center was independent of temperature changes at other refuse levels.

The temperature behavior pattern described indicates that the system was initially controlled by general aerobic conditions in the refuse, and that after a 60 day period, anaerobic conditions dominated. Also of interest is that once the internal temperatures became virtually steady state, and the refuse anaerobic, changes in top boundary temperature (bottom boundary temperature was held constant at 57.2^{o}F) had little effect on them.

Lysimeter Gases

Gas samples were analyzed on a routine basis for carbon monoxide, hydrogen sulfide, nitrogen, oxygen, carbon dioxide and hydrocarbons (reported as methane). No carbon monoxide or hydrogen sulfide were detected. The curves in Figures 48 through 51, for oxygen, carbon

TOP PORT

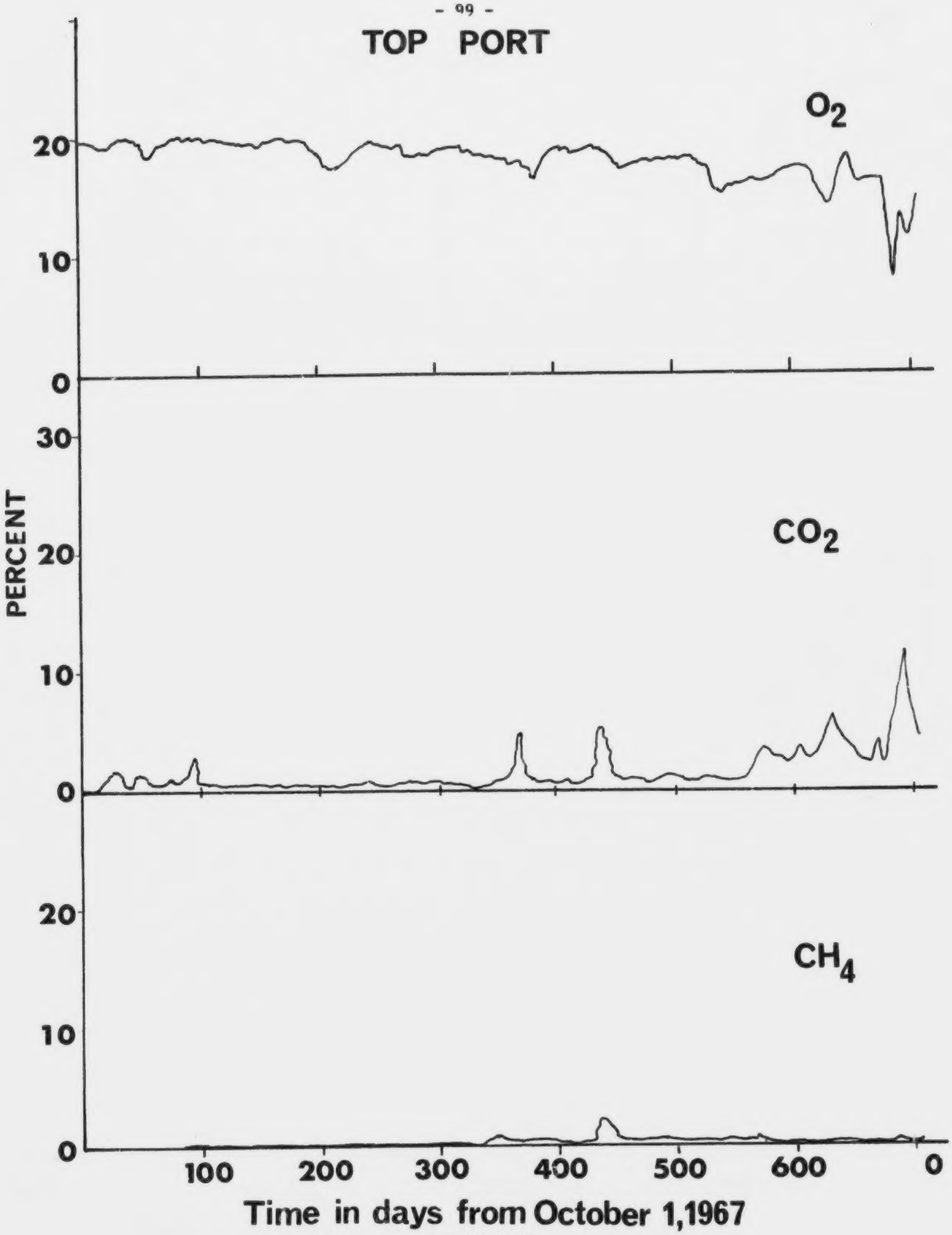


FIGURE 48

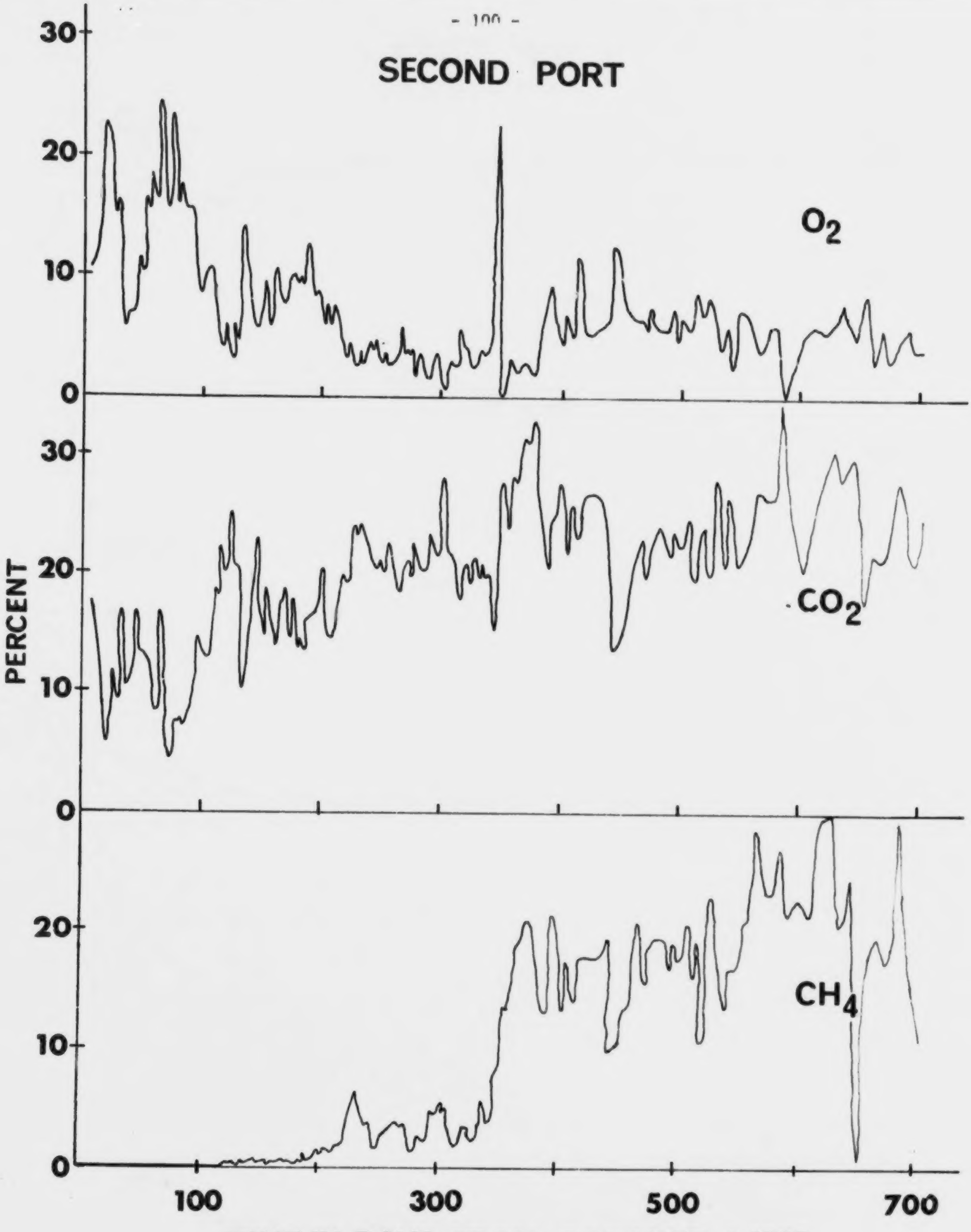
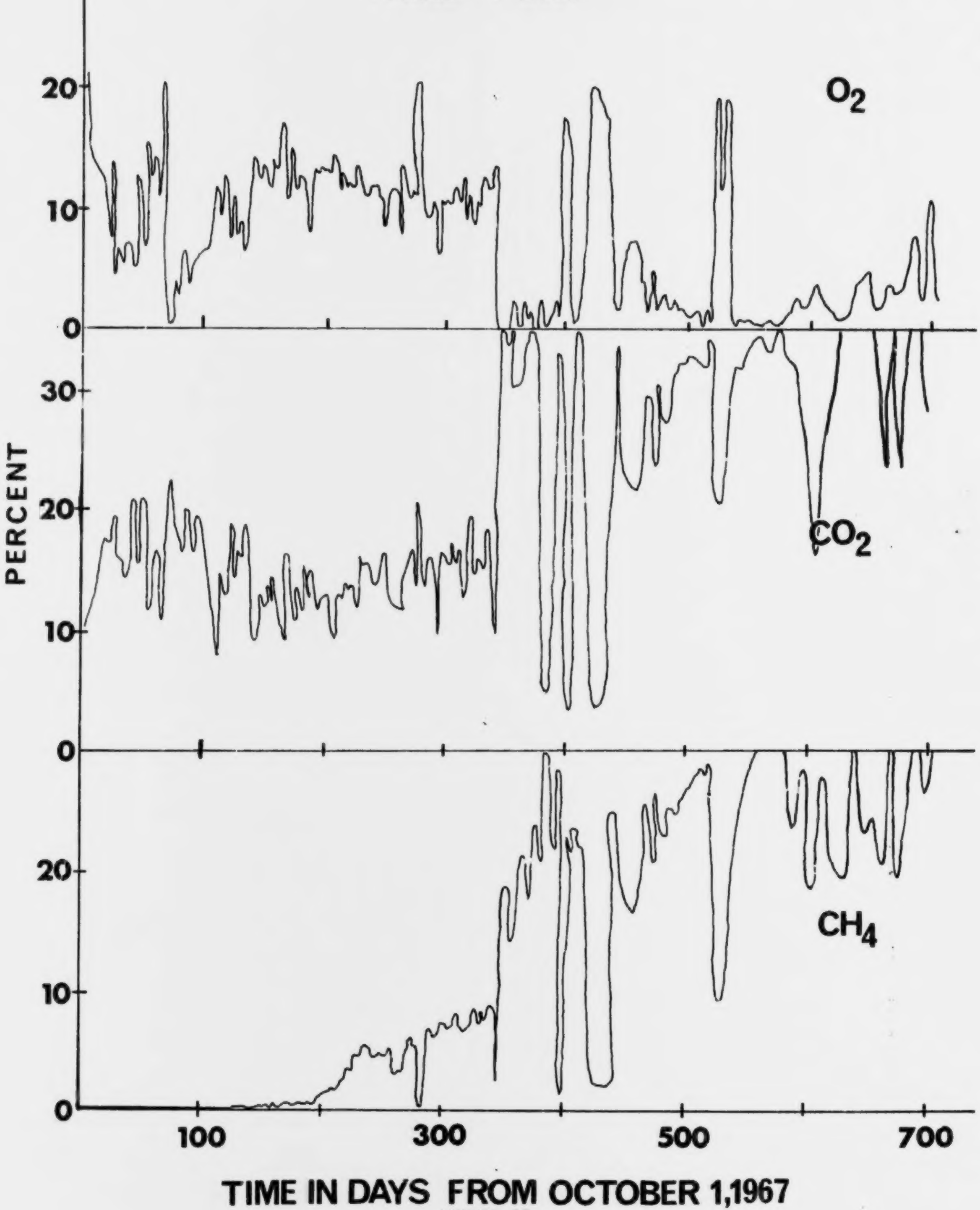

SECOND PORT
O$_2$
CO$_2$
CH$_4$
PERCENT
30
20
10
0
30
20
10
0
20
10
0
100
300
500
700
TIME IN DAYS FROM OCTOBER 1,1967

FIGURE 49



THIRD PORT

FIGURE 50

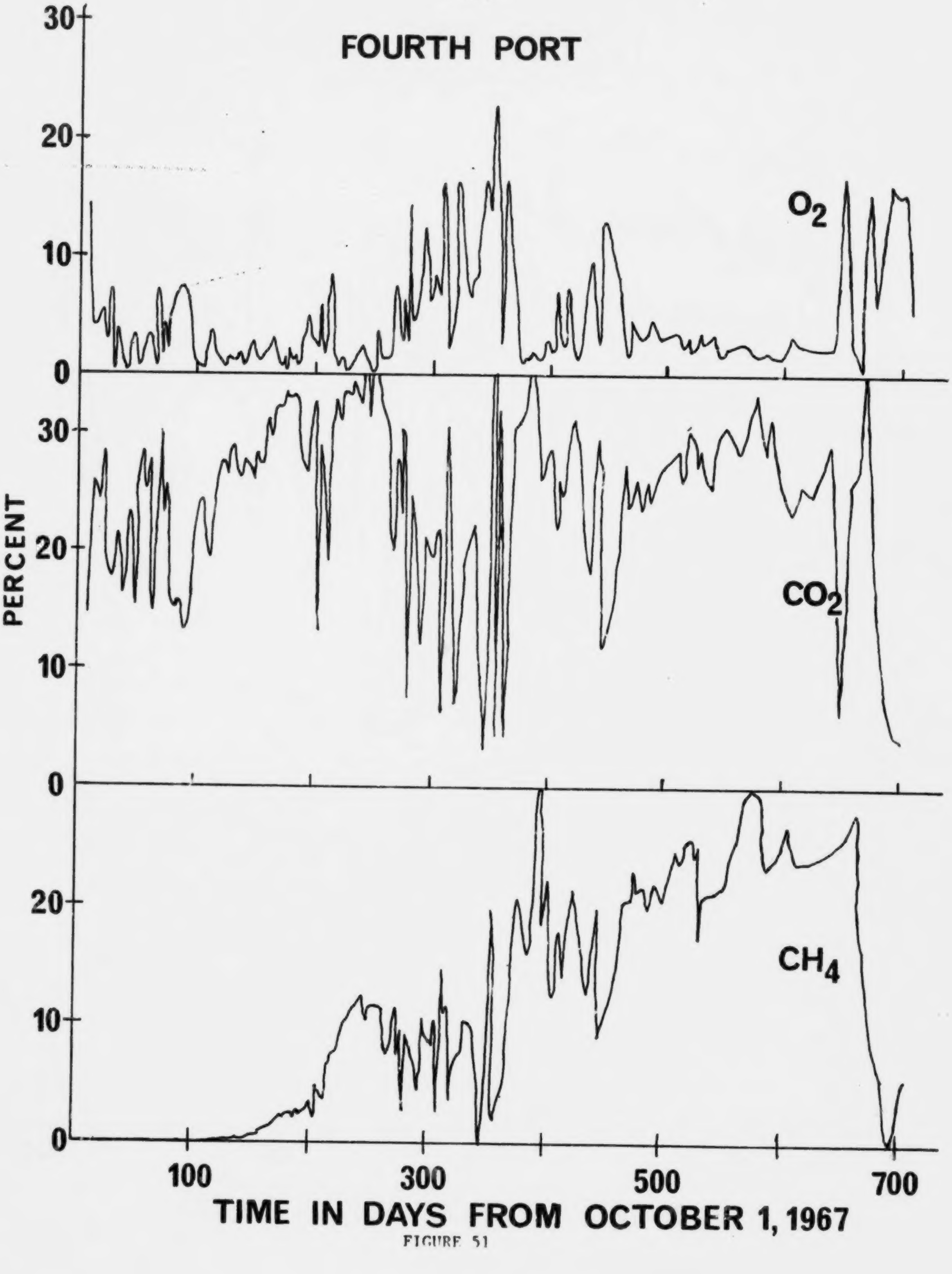

FOURTH PORT
30
20
10
0
30
20
10
0
20
10
0
PERCENT
O_2
CO_2
CH_4
100
300
500
700
TIME IN DAYS FROM OCTOBER 1, 1967

FIGURE 51

dioxide and methane are presented as percentage of total gas present at the time of sampling. Nitrogen, which made up the remaining percentage of the total, is not reported on the curves.

The curves presented in Figure 48 for the top port indicate a percentage of oxygen approximately equal to that contained in air. It is believed that the concentration level was due to settlement of the refuse in the lysimeter, which positioned the sampling port in or adjacent to the atmsopheric air space. This can only be verified upon test completion (at the time of this report, the lysimeter had not been opened). In general, gases present at the greater depths in the refuse were not detected (except in minor quantity) in the top gas sampling port.

Figures 49, 50 and 51 present gas curves for the other sampling ports of relatively similar patterns. Other levels tended to decrease with time and depth, while there was a corresponding increase in carbon dioxide and methane. Significant quantities of methane began to appear 100 days after initiation of the test. However, oxygen, while decreasing in quantity, was detectable over all of the test period. Carbon dioxide was present over the entire test period in amounts which increased slightly with depth.

Methane quantities increased with depth and time. At the second level they were as high at twenty eight percent although a more frequently determined maximum was approximately twenty percent. With increasing depths, maximum values frequently reached thirty percent.

From the temperature data (Fig. 47), it is seen that after the initial transient condition, internal temperatures decreased and were almost non-varying. This behavior indicates the existence of an anaerobic state within the refuse after the initial high temperature period. However, gas data, particularly the continued existence of oxygen, indicates that an aerobic state also existed in the refuse. From this data, it is concluded that pockets of aerobic and anaerobic activity existed concurrently within the refuse. Temperature and gas curve patterns indicate that the system was becoming more anaerobic with age. That such a behavior pattern existed is not surprising for a young landfill.

While the hydro-carbon gas is reported as methane, the accumulation of increasing percentages with depth indicates that it probably was a denser, higher molecular weight material than methane. No attempt was made to define the exact molecular structure of the gas. The lack of significant methane gas in the top port indicates little migration of the gas occurred, an observation which also supports the contention that the gas was a higher hydro-carbon.

It is noteworthy that gas character was more indicative of the internal biological activity and landfill age than internal temperatures.

Sanitary Landfill Field Facility

Background ground water quality data was collected since the Fall of 1967. Complete data for wells 1 through 11 are summarized in the data volumes. Concentration ranges for the varous ions are tabulated in Table 9.

Refuse was placed in the field test pit in May 1968. After that time, gas, soil-moisture and ground-water samples were collected on a regular basis.

TABLE 9

Background Data - Ground-Water Quality
Kennett Square Field Landfill

Ion	Range - mg/l
Iron	0.00 - 0.46
Zinc	0.00 - 1.38
Nickel	0.00 - 0.13
Copper	0.00 - 0.07
Total Dissolved Solids	40.00 - 1.30
Alkalinity	9.00 - 52.00
Hardness	20.00 -112.00
Phosphate	0.00 - 0.50
Sulfate	2.00 - 6.00
Chloride	4.00 - 28.00
Sodium	5.00 - 52.00
Suspended Solids	19.00 -208.00
Ammonia Nitrogen	0.00 - 0.00
Organic Nitrogen	0.00 - 1.50
Chemical Oxygen Demand	21.00 -200.00
Residue	80.00 -330.00
pH	5.30 - 7.00

Ground-water pollutant levels did not show a significant increase because the entire landfill had not reached field capacity at the time of this report. Results of analyses are summarized in the data volumes. Reported in this section are typical temperature and gas data for various levels within the refuse.

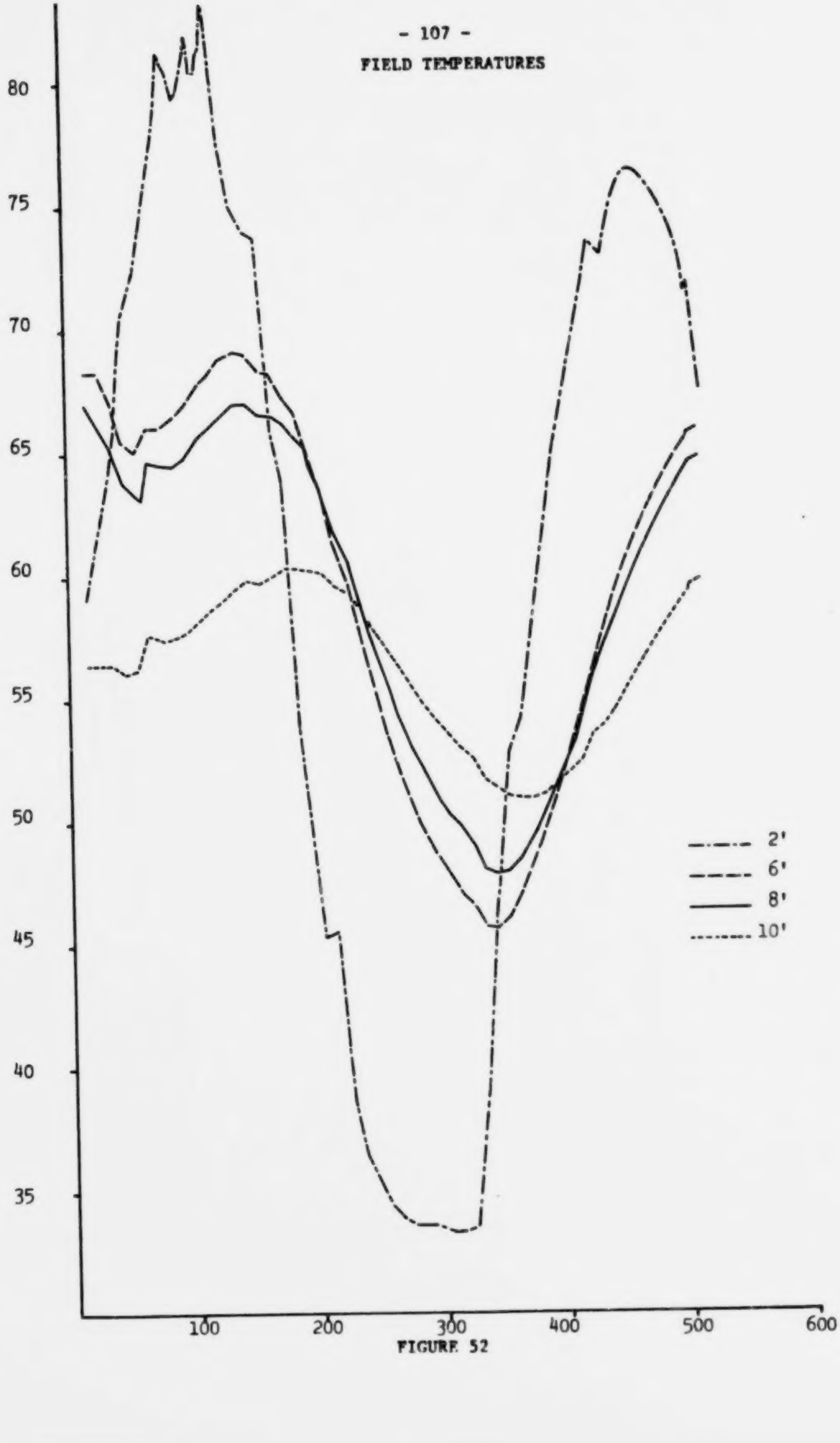
Field Temperatures

Figure 52 presents temperature curves which represent the average of four sensors at each level within the refuse. The two foot depth sensor curve shows maximum response to atmospheric temperatures. The curves for the other depths indicate that during the reported time period, internal temperatures had a highly modulated phase response to atmospheric and ground temperatures. The results indicate very little initial biological activity within the refuse (as compared to the lysimeter). It is believed that the initial temperature behavior pattern is a result of the relatively high refuse placement density.

Field Gases

Gas samples were analyzed on a routine basis for carbon monoxide, hydrogen sulfide, nitrogen, carbon dioxide and hydro-carbons (reported as methane). No carbon monoxide or hydrogen sulfide was detected. The curves in Figures 53 through 55, for oxygen, carbon dioxide and methane are presented as a percentage of total gas present at the time of sampling. Nitrogen, which made up the remaining percentage of the total, is not presented on the curves.

The curves show an initial high percentage of carbon dioxide at the various depths followed by lower values, with isolated peaks, for



FIELD TEMPERATURES

FIGURE 52

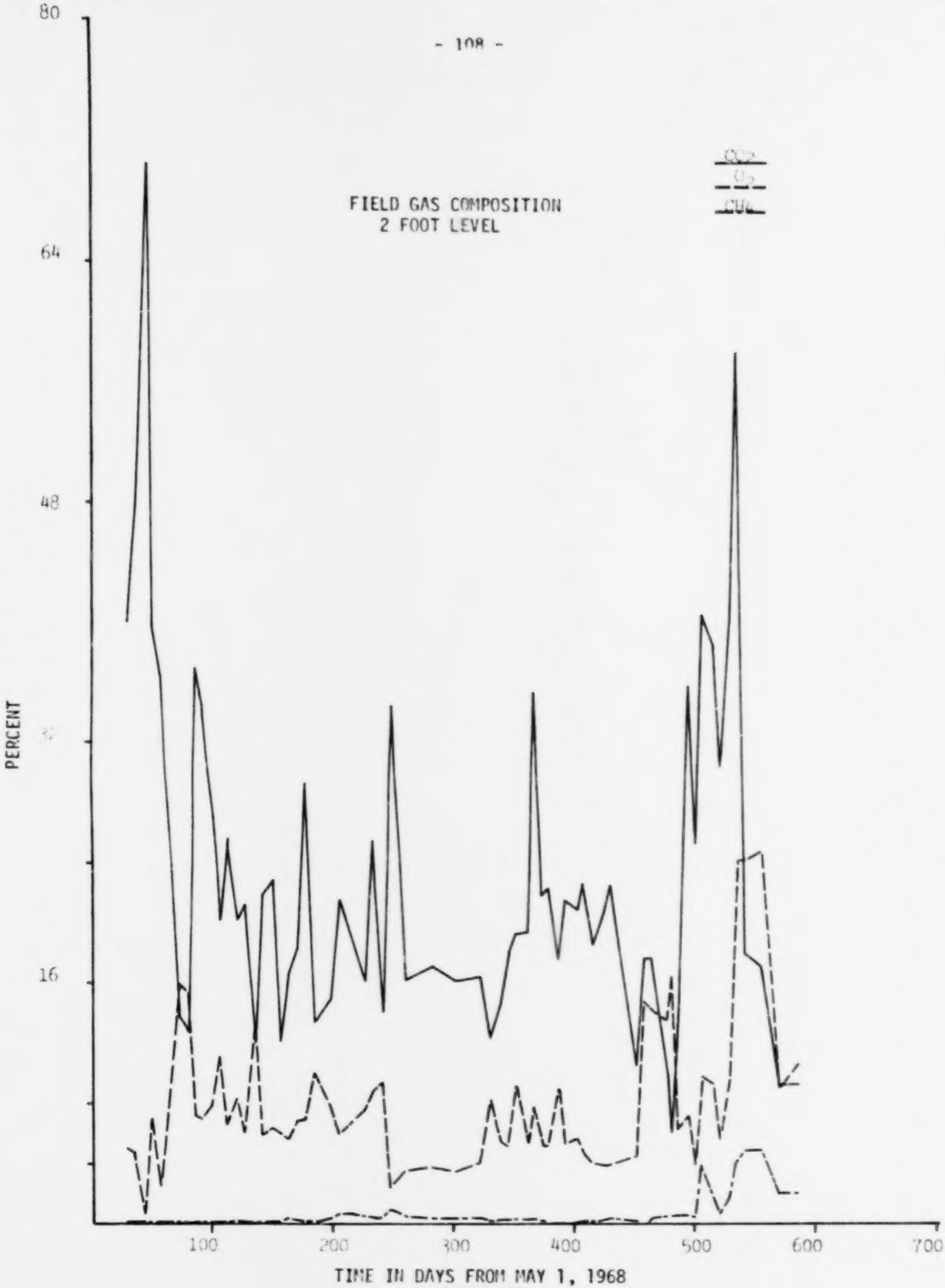

FIELD GAS COMPOSITION
2 FOOT LEVEL
CO2
O2
CH4
PERCENT
80
64
48
32
16
100
200
300
400
500
600
700
TIME IN DAYS FROM MAY 1, 1968

FIGURE 53

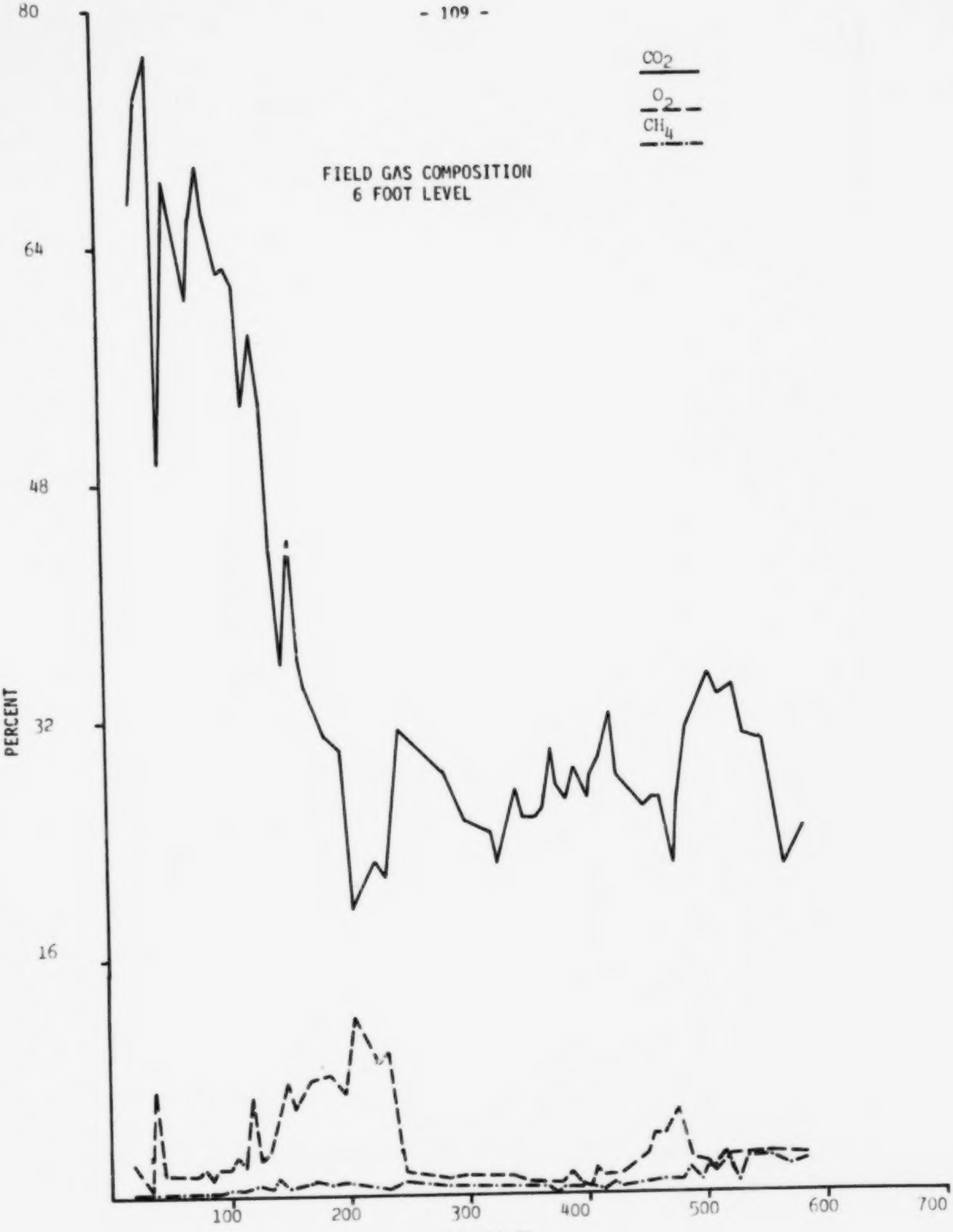

FIELD GAS COMPOSITION
6 FOOT LEVEL
CO_2
O_2
CH_4
PERCENT
80
64
48
32
16
100
200
300
400
500
600
700

FIGURE 54

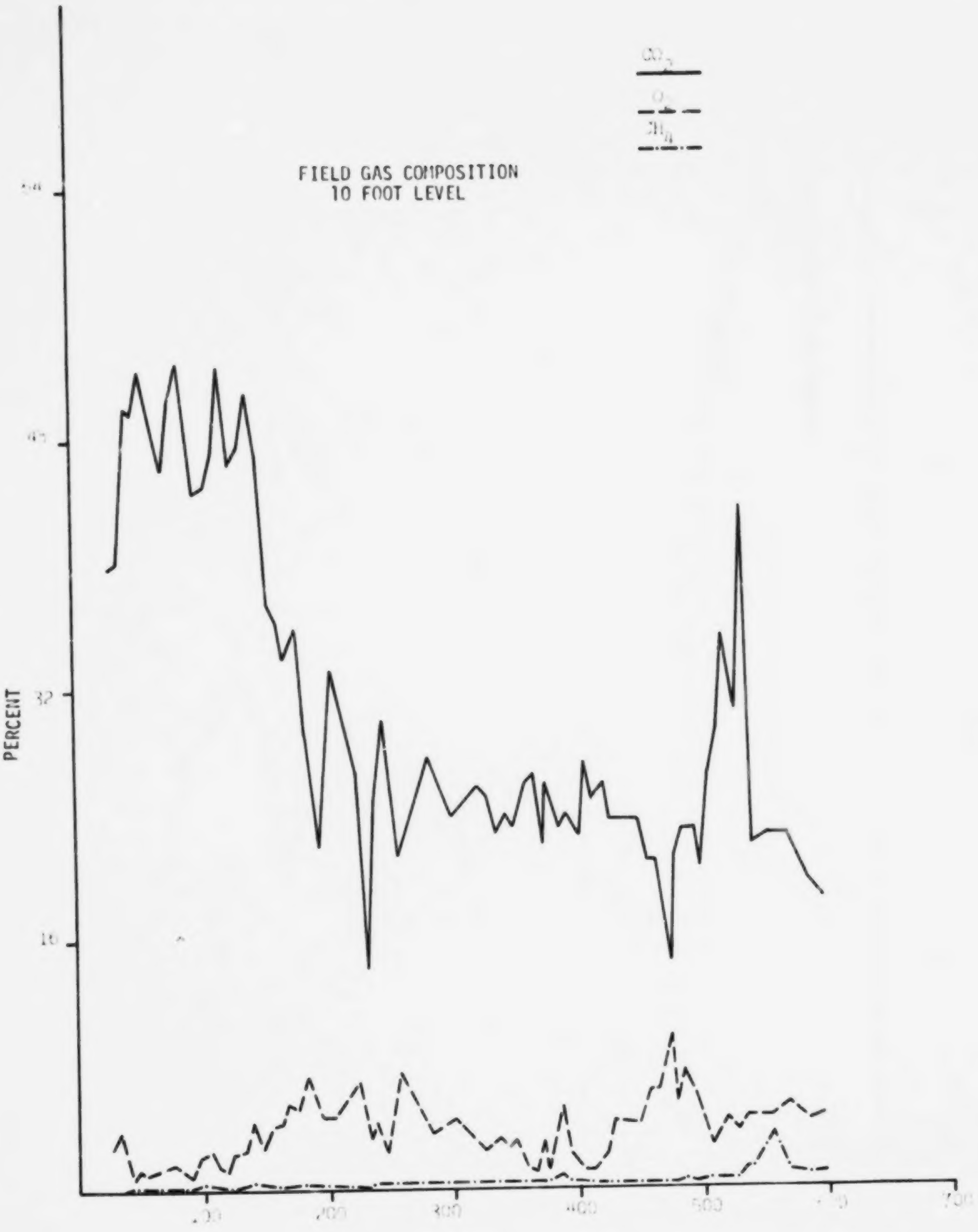

FIELD GAS COMPOSITION
10 FOOT LEVEL
CO_2
O_2
CH_4
PERCENT
64
48
32
16
100
200
300
400
500
600
700

FIGURE 55

the remainder of the test period. Oxygen and methane levels were relatively low. The trends of the various gases are very erratic; a pattern which is believed to be due to the dynamic behavior of the landfill because of its young age.

LIQUID POLLUTANT GENERATION BY AN UNSATURATED SANITARY LANDFILL

The generation of liquid pollutants by an unsaturated sanitary landfill is dependent upon the content, spacial distribution and time variation of moisture within that landfill. Therefore, knowledge of the factors which control moisture movement is basic to a knowledge of the generation and movement of water-borne contaminants. Presented in this section are a moisture routing model and a discussion of some of the primary factors which control leachate generation. Included in the discussion are a computer program for evaluating the model, the results of some specific site studies, and a simplified procedure for approximating liquid pollutant quantities.

MOISTURE ROUTING MODEL

Theory

The model is for a one-dimensional, downward vertical flow system. Water input is due to surface infiltration. The moisture routing procedure is based upon using the equation of continuity for predicting the hydrologic performance of any soil layer. For determining water movement, the equation of continuity is of the form:

$$\Delta\Theta = Q_I - Q_0$$

where,

$\Delta\Theta$ = change in water storage in that layer,

Q_I = the water flow into the layer; and

Q_O = water flow out of the layer.

In the case of a landfill, the uppermost cover soil layer obtains moisture usually by precipitation and loses moisture by evapotranspiration and vertical downward drainage. In underlying layers, moisture is added by drainage from overlying layers. It is removed from underlying layers by drainage to still lower layers or by evapotranspiration, if roots penetrate to, or almost to, the layer. To solve the water-routing problem, knowledge of the landfill's hydraulic characteristics is required. Two quantities must be determined, usually by experimental evaluation: field capacity and permanent wilting percentage.

Field Capacity

Defined herein as the maximum moisture content which a soil or refuse can retain in a gravitational field without producing significant leachate.

The field capacity of a soil or refuse can be estimated by subjecting it to a capillary suction head of approximately 100 cm. of water. Water applied to a soil at a moisture content greater than field capacity drains rapidly to the lower surface. At this lower surface, it either enters into underlying materials or appears as a leachate. When the moisture content has decreased to field capacity, the soil or refuse remains essentially at that moisture content, unless it loses moisture in other ways.

Permanent Wilting Percentage

Defined as the moisture content below which moisture is unavailable for withdrawal by plants.

The permanent wilting percentage for a soil or refuse can be approximated by subjecting it to the equivalent of a suction of 15 atmospheres. To reach permanent wilting percentage, the soil or refuse must be near the land surface or within the plant-root zone.

When the moisture content of a soil or refuse is below field capacity, a moisture application will not distribute itself uniformly throughout that soil or refuse. Rather, each layer of material must reach field capacity before significant quantities of water drain to underlying material. The mass of percolating water is preceded by a wetting front or region of steep-moisture content gradient.

The moisture range between field capacity and the permanent wilting percentage, or initial moisture content (whichever is greater) is referred to as available water. By determining the available water storage capacity of each soil and refuse layer, it is possible to apply the principle of continuity to moisture routing through a sanitary landfill.

The physical system outlined above is an initial and boundary value problem. The solution of such a problem is achieved by solving the equation of continuity taking into consideration the appropriate initial and boundary conditions. To obtain a solution for a particular sanitary landfill system, the continuity equation is solved taking the hydraulic characteristics of the soil and refuse and the environmental conditions on the upper surface as boundary conditions and the initial moisture contents as initial conditions.

Moisture Routing Computer Model

The complete program listing for the computer model to route moisture vertically through an unsaturated landfill is presented in Appendix 5. In brief, the model includes three zones in the landfill (Fig. 56): a top soil zone, which is subject to environmental conditions; an underlying zone of soil, which is defined as a passive zone not subject to environmental conditions; and the underlying refuse layer. A complete discussion of the computational procedure is given in Reference 13.

Application of Computer Model Program

The computer model program has been used to evaluate several landfill systems. One system is the laboratory simulated landfill. A second system is the landfill at the field installation in Kennett Square. In addition, the program has been used to evaluate the first appearance of leachate for a variety of environmental conditions.

Laboratory Simulated Landfill

The results of this study are presented in Figure 57. While there is a variation between predicted time and actual time of appearance of significant leachate, the results indicate a high degree of correlation. The difference between the predicted time and the actual time is due to the following:

1. The system does not behave exactly like the theoretical field capacity model; that is, no downward movement of moisture until field capacity is attained in a particular layer (see Fig. 18).
2. The refuse field capacity probably changes during its life cycle.
3. The refuse field capacity and initial moisture content data are, at best, only reasonable approximations due to the material's heterogeneous nature.

SCHEMATIC OF SOIL-REFUSE SYSTEM

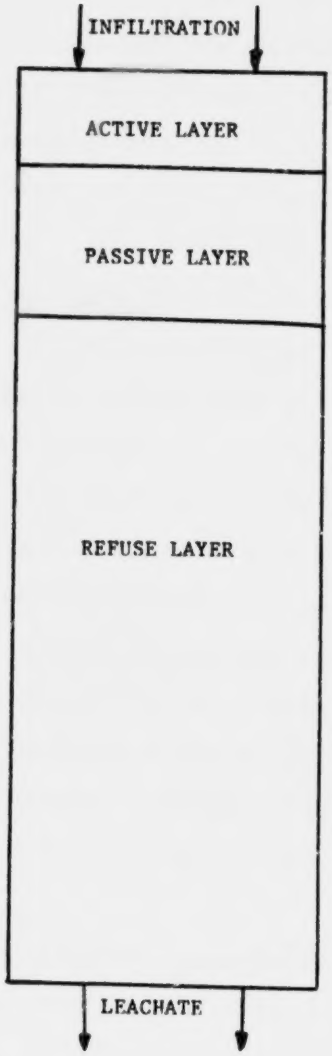


FIGURE 56

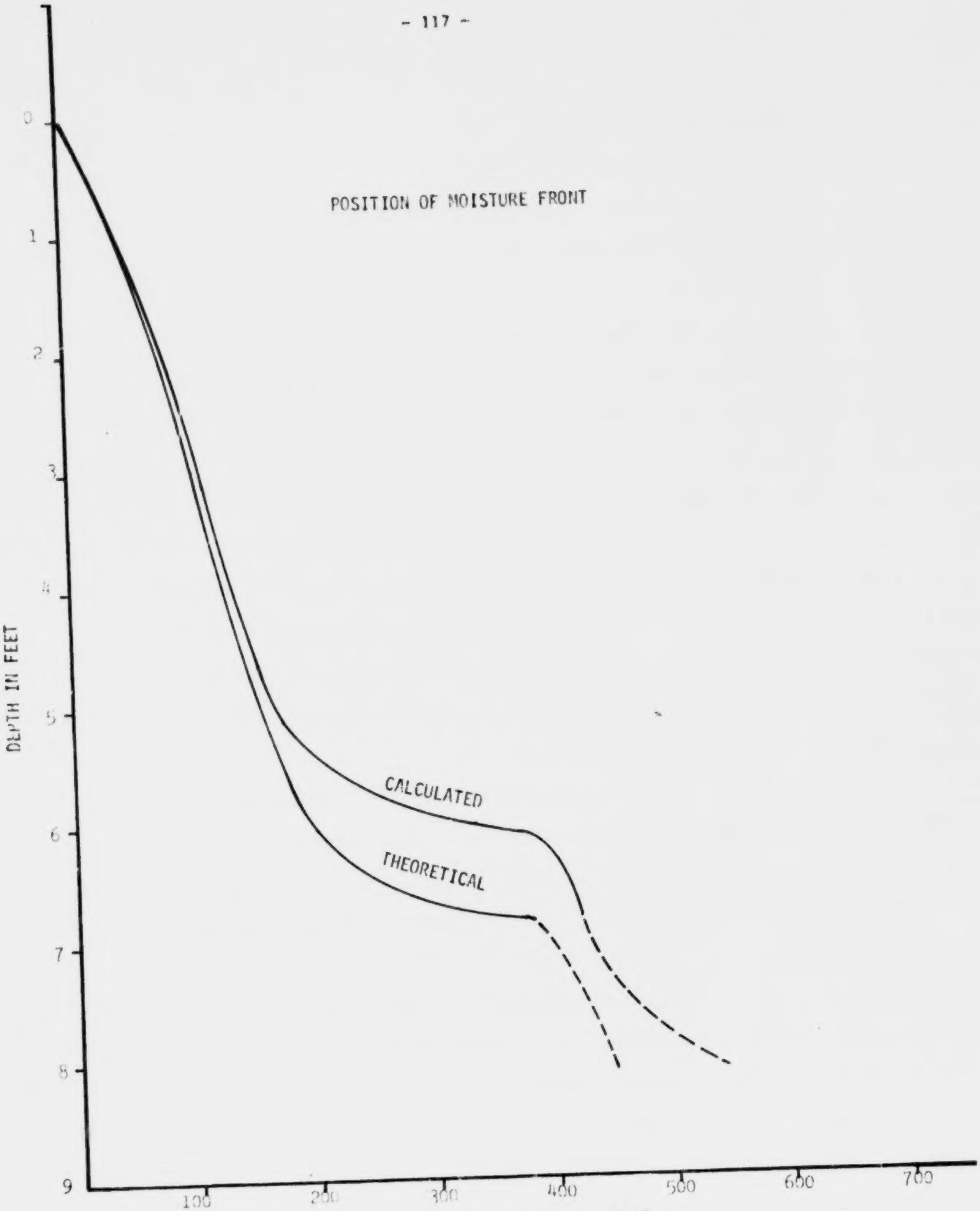

POSITION OF MOISTURE FRONT
DEPTH IN FEET
0
1
2
3
4
5
6
7
8
9
CALCULATED
THEORETICAL
100
200
300
400
500
600
700
TIME IN DAYS FROM OCTOBER 1, 1969

FIGURE 57

Kennett Square Landfill

a. Field Conditions

The landfill consists of eight feet of compacted refuse and a two-foot-thick soil cover. The soil cover is Glenelg-Channery silt loam.

While a prediction of the behavior of the in-situ landfill was performed, at the time of this report the field site had not reached field capacity. The results of this study will be reported at a later date.

b. Hypothetical Conditions

Laboratory determinations on undisturbed field samples of the cover soil gave a field capacity moisture content of 0.349 on a volume basis and a permanent wilting percentage moisture content of 0.090 on a volume basis. Therefore, maximum available water was 0.259 on a volume basis, or 6.20 inches of water per unit area for a two-foot-thick soil cover.

The refuse was patterned after the results of Kaiser (10). Based on asbestos tension table tests at an initial compacted refuse density of 485 pounds per cubic yard, field capacity moisture content was 0.286 on a volume basis, and the initial moisture content was 0.039 on a volume basis.

The environmental data is presented in Table 1 and the system analysis was simplified by the following assumptions:

1. The fill surface was fully vegetated at all times by plants whose roots drew water directly from all parts of the soil cover, but not from the underlying refuse.

2. No moisture was removed by diffusing gases.

3. All rainfall infiltrated the land surface.

4. The hydraulic characteristics of the soil cover and compacted refuse were uniform in all directions.

5. The landfill and underlying soil were free draining.

6. The depth of the landfill was much less than its horizontal extent. Therefore, all water movement was vertically downward.

7. The refuse and cover were emplaced instantaneously on the first day of the month of the computation initiation.

The results of the analysis of four landfill conditions are presented in Table 10 and are summarized below.

CASE 1 - EMPLACEMENT OF ALL MATERIALS AT FIELD CAPACITY ON JANUARY 1.

> When the components of the system are initially at their respective field capacities and the materials are emplaced during the wet season, leachate will appear immediately.

CASE 2 - EMPLACEMENT OF ALL MATERIALS ON JANUARY 1 WITH THE SOIL COVER AT PERMANENT WILTING PERCENTAGE AND THE REFUSE AT ITS NATURAL MOISTURE CONTENT.

> By emplacing the soil cover at its permanent wilting percentage and the refuse at its initial moisture content during the wet season, leachate appearance can be delayed for thirteen months.

CASE 3 - EMPLACEMENT OF ALL MATERIALS AT FIELD CAPACITY ON JULY 1.

> When the components of the system are initially at their respective field capacities and the materials are emplaced during the dry season, leachate appearance can be delayed only until the beginning of the next wet season.

CASE 4 - SAME AS CASE 2 BUT WITH EMPLACEMENT ON JULY 1.

> By emplacing the soil cover at its permanent wilting percentage and the refuse at its initial moisture content during the dry season, leachate appearance can be delayed twenty months.

TABLE 10

Leachate Quantities (In Inches) From Kennett Square Sanitary Landfill For Four Different Emplacement Conditions

CASE	JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER
							YEAR 1					
1	3.40	2.95	3.40	1.66	0.18	0.00	0.00	0.00	0.00	0.00	1.75	3.03
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3							0.00	0.00	0.00	0.00	1.75	3.03
4							0.00	0.00	0.00	0.00	0.00	0.00
							YEAR 2					
1	3.40	2.95	3.40	1.66	0.18	0.00	0.00	0.00	0.00	0.00	1.75	3.03
2	0.00	0.00	2.28	1.66	0.18	0.00	0.00	0.00	0.00	0.00	1.75	3.03
3	3.40	2.95	3.40	1.66	0.18	0.00	0.00	0.00	0.00	0.00	1.75	3.03
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
							YEAR 3					
1	3.40	2.95	3.40	1.66	0.18	0.00	0.00	0.00	0.00	0.00	1.75	3.03
2	3.40	2.95	3.40	1.66	0.18	0.00	0.00	0.00	0.00	0.00	1.75	3.03
3	3.40	2.95	3.40	1.66	0.18	0.00	0.00	0.00	0.00	0.00	1.75	3.03
4	0.00	0.00	3.27	1.66	0.18	0.00	0.00	0.00	0.00	0.00	1.75	3.03

Landfill Performance for a Variety of Environmental Conditions

Landfill behavior was evaluated at eight different sites. The results of this evaluation are presented in Table 11. These results are based on 30 year average rainfall and temperature data for the particular region. The landfills consist of 8 feet of refuse and a 2 foot soil cover, with the physical parameters listed in the table.

The results indicate that there is wide variation in the first appearance of leachate, but that as long as there is a net infiltration, leachate will appear. Again, changes in physical structure, such as that due to grinding, will have a marked influence on the time required for first leachate appearance.

Refuse Field Capacity

In Figure 58, results of field capacity tests on refuse are presented. The top data points (squares) represent finely ground refuse. This refuse had an effective size of 3/16 of an inch and was prepared from raw domestic refuse using a Williams Laboratory Bench Grinder. The data represented by the dots is for refuse ground to an effective size of one inch using a Williams Hammermill. Field capacity data obtained from other reported studies (8, 14) and the laboratory lysimeter are also shown.

The results show:

1. That as the refuse size decreases, field capacity increases significantly.

2. That with increasing dry density, the increase of field capacity will approach asymptotically a maximum which is size-dependent.

It is concluded from these studies that the influence of grinding is to greatly increase soil field capacity; hence, retard the first appearance of leachate from a landfill constructed of such material.

TABLE 11

Computed Elapsed Time to First Appearance of Leachate

City	Elapsed Time in Months
Wilmington, Delaware	24
Philadelphia, Pennsylvania	25
Mobile, Alabama	15
Sacramento, California	50
Los Angeles, California	145
Bismark, North Dakota	-
Riverside, California	-
Phoenix, Arizona	-

NOTES:

1. Based on average 30-year rainfall and temperature data for each area.
2. Refuse and Soil Data:

	Refuse	Soil
Field Capacity (in/ft)	3.49	4.18
Original Moisture Content (in/ft)	0.46	1.08
Depth (feet)	8.00	2.00

3. Placement data: October 1

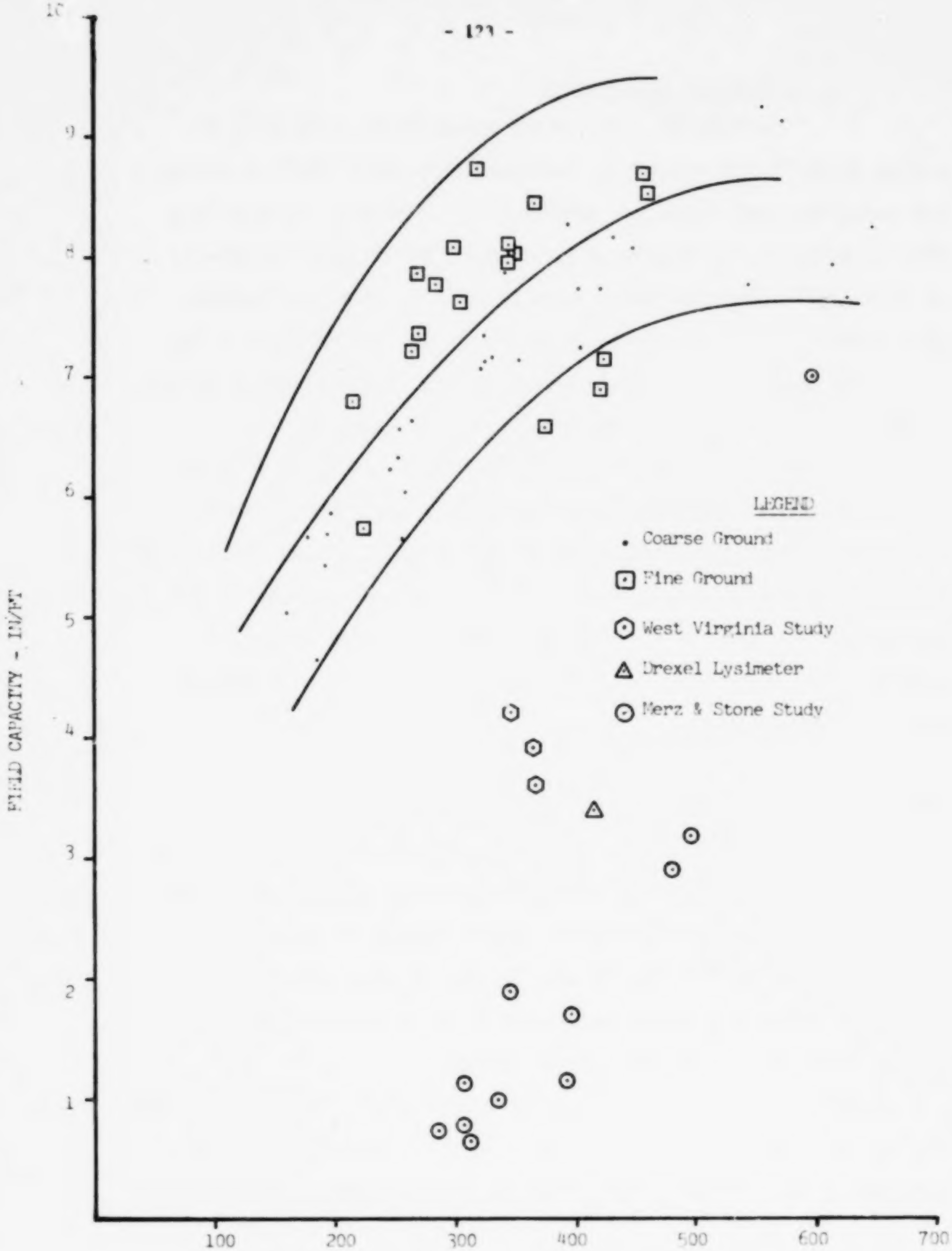

FIELD CAPACITY - IN/FT
10
9
8
7
6
5
4
3
2
1
100
200
300
400
500
600
700
DRY DENSITY - LBS/YD³
LEGEND
• Coarse Ground
⊡ Fine Ground
West Virginia Study
△ Drexel Lysimeter
⊙ Merz & Stone Study

FIGURE 58

U. S. Potential Infiltration

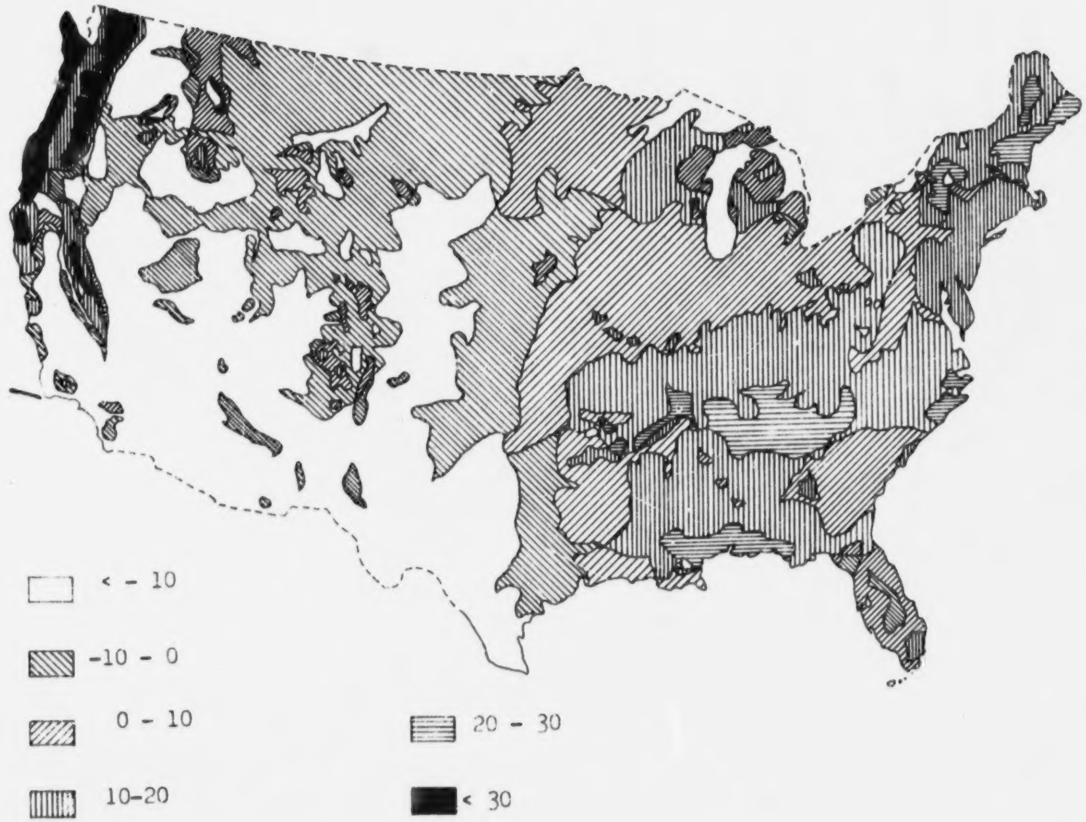
In Figure 59, a map of the United States with a plot of average potential infiltration is presented. This map is based on rainfall and evapotranspiration data from Reference 15. In general, it shows that there is potential infiltration of water into landfills over the majority of the United States. As long as there is a net infiltration, leachate will eventually begin to be produced by a landfill. The magnitude of the quantity of actual infiltration depends on surface draining characteristics, surface grading, surface treatment and planting of vegetation.

It must be noted that this map is representative of average conditions; that is, conditions which average out over a year's span. The data presented in this map should not be used to evaluate quantities or first appearance of leachate. Rather, it should be used as an indicator of the magnitude of the potential. To evalute a specific site or specific conditions requires utilization of the moisture routing model using site physical characteristics.

GRAPHICAL PROCEDURE FOR PREDICTING FIRST APPEARANCE OF LEACHATE

The procedure described can be used to approximately predict the first appearance of leachate once the soil cover and refuse physical properties are known. This procedure is a first estimate because the data is based on average annual infiltration values. It does not take into consideration conditions such as high summer evapotranspiration or concentrated rain storms. Further, the soil data are approximate.

Figure 60 presents data which can be used to predict the passage of water through the cover soil in months. These curves are for one inch infiltration per month to bring the soil from wilting to field capacity. It is assumed



AVERAGE POTENTIAL INFILTRATION - INCHES

FIGURE 59

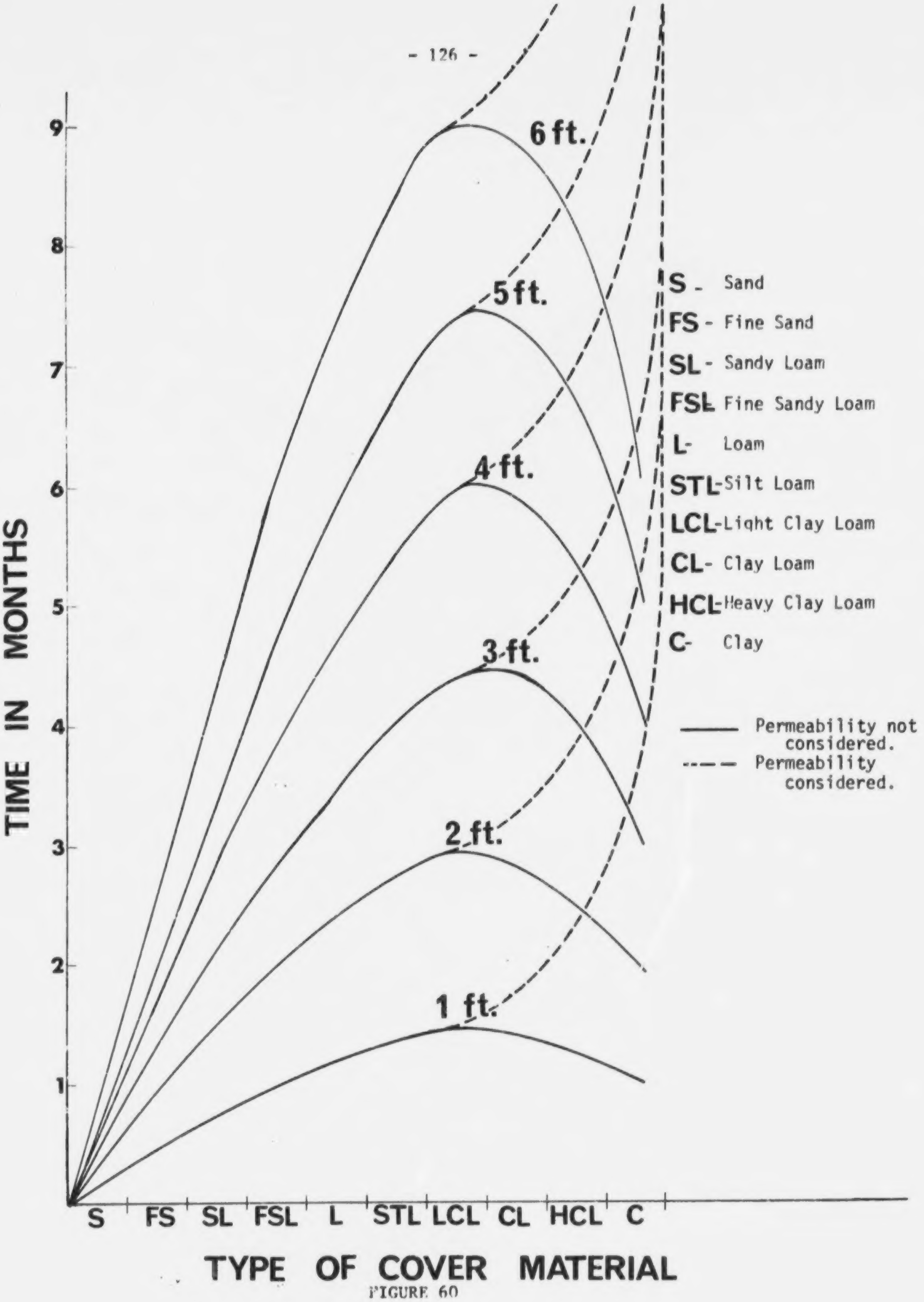

TIME IN MONTHS
9
8
7
6
5
4
3
2
1
6 ft.
5 ft.
4 ft.
3 ft.
2 ft.
1 ft.
S - Sand
FS - Fine Sand
SL - Sandy Loam
FSL Fine Sandy Loam
L- Loam
STL-Silt Loam
LCL-Light Clay Loam
CL- Clay Loam
HCL-Heavy Clay Loam
C- Clay
Permeability not considered.
Permeability considered.
S
FS
SL
FSL
L
STL
LCL
CL
HCL
C
TYPE OF COVER MATERIAL

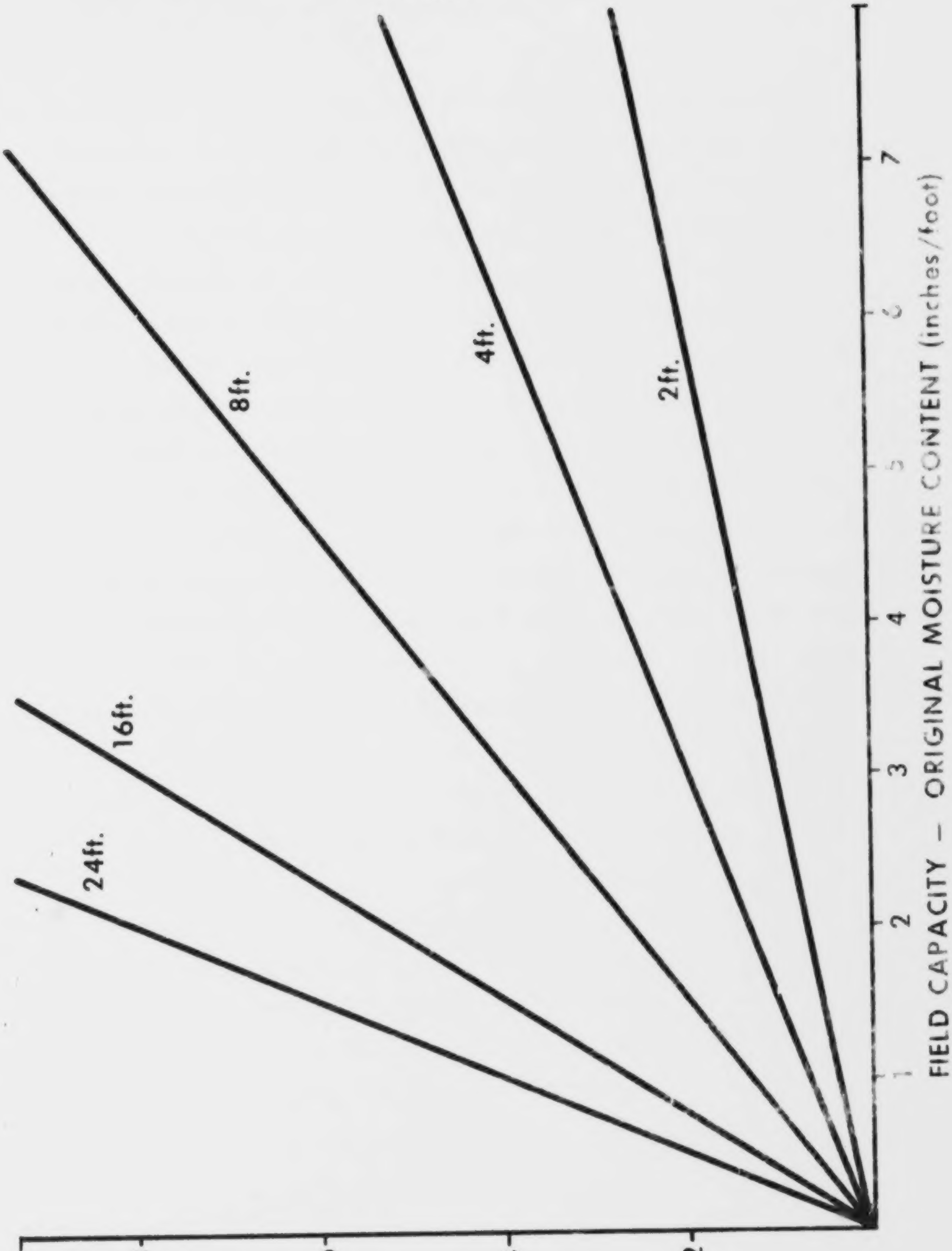
FIGURE 60

that the moisture content of the soil will never be less than the wilting moisture content. The numbers on the curves are for various thicknesses of soil cover from one foot to six feet. The abscissa represents different soil types and the ordinates are times for average conditions.

The curves in Figure 61 can be used to predict the time necessary for leachate to pass through the refuse where the abscissa are net infiltration (field capacity minus original moisture content) and the ordinates are in months. The numbers on the curve represent thickness of the refuse portion of the landfill. Thickness of intermediate soil covers are ignored in this computation. It is believed that this data would not have any significant effect on final results. However, if the field capacity or original moisture content of the intermediate soil covers varies significantly from that of the refuse, a weighted average could be used to determine the abscissa value.

The graphical procedure used to determine the appearance of leachate is as follows:

1. Routing through the soil cover
    a. Determine type of soil to be used for cover.
    b. Determine the thickness.
    c. Using Figure 60, evaluate the time from placement when leachate will pass through the soil cover if the soil is placed at the wilting moisture content.
    d. Calculate the moisture content of the soil, and time of placement in percent on a dry weight basis.


TIME IN MONTHS
56
48
36
24
12
FIELD CAPACITY — ORIGINAL MOISTURE CONTENT (inches/foot)
1
2
3
4
5
6
7
24ft.
16ft.
8ft.
4ft.
2ft.

e. $\frac{a \times b}{c}$

a = calculated time from Figure 60
b = Field Capacity - Placement Moisture Content
c = Field Capacity - Wilting Moisture Content

2. Routing through refuse
   a. Determine field capacity of the refuse.
   b. Determine the original moisture content of the refuse.
   c. Calculate water storage capacity of the refuse (field capacity - original moisture content).
   d. Determine depth of refuse.
   e. Using Figure 61, determine time from placement when leachate will appear at the bottom of the refuse.
3. Total time for leachate appearance
   a. Add times from computations 1 and 2.
   b. From Figure 59, determine the average filtration for a given area.
   c. Total time = sum of 1 and 2 x sum of average infiltration.

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This manual is based primarily on two preliminary manuals prepared for this project entitled:

"Analysis of Liquid Samples" by A. W. Lawrence[1]
"Analysis of Gas Samples" by N. Trieff[2]

The assistance of R. Schafish and G. Cox is hereby acknowledged.

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APPENDIX 1

Analytical Procedures for Chemical Pollutants

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Note: The procedures described herein apply to both the laboratory lysimeter and field installation sample.

LIQUID SAMPLES

The same analytical procedure is used to measure a given parameter in samples from both the lysimeter and the field installation. On the average, the lysimeter leachate will have higher concentrations. Therefore, these samples will generally have to be subjected to some form of pretreatment, i.e., dilution, neutralization, centrifugation, or filtration prior to analysis. The pretreatment to be used will be determined when a sample is being readied for analysis.

Reagent Preparation

Proper preparation of reagents is the foundation of meaningful and accurate analytical procedures. Maximum care should be taken in preparing reagents, especially those which are primary standards and whose strength cannot be easily checked. Most chemicals are dried at 103°C before weighing a specific quantity. Deionized water must be used in the preparation of all reagents. Particular attention must be paid to information contained in "Standard Methods for the Examination of Water and Wastewater",[1] (hereafter denoted as S.M.) regarding the stability or "shelf life" of reagents, "for it is far better to discard doubtful reagents than to analyze in vain".[2] An excellent description of the procedures used in preparing standard solutions is found in chapter 14 of "Chemistry for Sanitary Engineers".[3] In case of critical shortages of personnel and/or time, many reagents may be purchased from chemical suppliers, already prepared and standardized; however, such reagents are quite expensive.

Important in the preparation of reagents is the accurate weighing of micro-quantities of material. Each analyst should be thoroughly familiar with the operation of the Mettler (or equivalent) analytical balance. Most materials are weighed after drying at 103°C and cooled in a desiccator. It is important to complete a weighing rapidly due to the adsorption of moisture during weighing.

pH

pH is determined by the Glass Electrode Method as described on page 225 of S.M. A line operated Beckman Expanded Scale pH meter is used in this determination. An Orion single junction reference electrode filled with 10% KNO_3 replaces the standard calomel electrode. The normal limits of accuracy reported for this method are ± 0.1 pH unit.

Additional notes on pH appear in Appendix A.

Alkalinity

Alkalinity is determined in accordance with the procedure described on page 48 of S.M. with the following modifications:

1. A fifty milliliter (ml) sample is used.
2. 0.02 N H_2SO_4 (or lesser concentration, depending on the magnitude of the alkalinity) is used as the titrant.
3. The sample is stirred by a magnetic stirrer during the titration.
4. The sample is titrated to a pH value determined by the magnitude of the alkalinity. The reported standard deviation for alkalinity determinations in sewage with colorimetric endpoint indicators and 0.02N H_2SO_4 reagent is 0.07 ml.

In the procedure used here, an increase in titration precision should result from the potentiometric endpoint determination while a decrease in overall precision should result from the use of a more concentrated titrant.

Additional notes on alkalinity appear in Appendix A.

Suspended Solids

Suspended solids are determined by leachate filtration through a glass fiber filter pad. The analytical procedure employed is essentially the same as that described by Wyckoff[4] for the determination of suspended solids in sewage and activated sludge. The glass fiber filter pads used are 4.25 cm. Whatman Glass Paper, grade GFC manufactured by W. and R. Balston, Ltd. of England and obtained from Scientific Glassware Co., Bloomfield, N. J. During filtration, the filters are supported by a Pyrex glass filter holder assembly, Model No. 04700, manufactured by Millipore Filter Corporation, Bedford, Mass. Following filtration, the pads are weighed after being dried for one hour at 103°C and again after being ignited for ten minutes at 600°C. Blank filter pads are carried through the procedure with each set of samples to allow a correction to be made for the initial moisture content of the filter pads.

Smith and Greenberg[5] evaluated five different filtration techniques for the determination of suspended solids in sewage. These techniques included glass fiber filter pads supported in different ways, membrane filter pads, and the "standard method" employing the Gooch crucible with asbestos mat. The suspended solids content of several sewage samples was determined by each technique. On the basis of a statistical analysis of variance, it was concluded that all five techniques yielded results which were not statistically different. On a non-statistical basis, a glass fiber filter technique was indicated as the method of choice. The coefficient of variation calculated from the determinations by Wyckoff[4] of suspended solids in activated sludge effluent is 11.2

percent for total solids and 13.8 percent for volatile solids.

Additional information concerning this procedure appears in Appendix B.

Nitrogen

Ammonia

Ammonia nitrogen is determined according to the procedure described on page 389 of S.M. with the following modifications:

1. The sample volume is 15-375 ml.
2. The distillate is collected in boric acid solution and titrated to a colorimetric-determined endpoint at pH 4.5 if the NH_3-N concentration is $\leq$ 5 mg/l.

It is reported that this method recovers 99-100 percent of the available ammonia with a precision, expressed as the titration standard deviation, of 0.18 ml. over the concentration range of 5-50 mg/l NH_3-N.

Organic Nitrogen

After the ammonia nitrogen distillation, the remaining liquid is analyzed for organic nitrogen, according to the method described on page 402 of S.M. with the following modification: one $HgCl_2$ catalyst tablet and 10 ml conc. H_2SO_4 replaces the Acid-Catalyst Solution. The reported recovery and precision for this method in the concentration range of 5-50 mg/l organic nitrogen are 98.5 - 99.5 percent and ± 0.13 mg/l respectively.

Chemical Oxygen Demand

The chemical oxygen demand (COD) of liquid samples is determined by the dichromate reflux method described on page 510 of S.M. with the following modifications:

1. Sample and reagent volumes used are 20 ml. aliquot, 5 ml. of 0.5 N $K_2Cr_2O_7$, and 15 ml. of H_2SO_4 (with Ag_2SO_4).

2. The silver sulfate catalyst is employed in all determinations.

3. Mercuric sulfate (0.4 grams per sample) is added to all samples to eliminate the need for chloride corrections.

It is reported that this method oxidizes most compounds to 95-100 percent of the theoretical oxygen demand. With the silver sulfate catalyst, short straight chain alcohols and acids are oxidized to 85-95 percent or more of the theoretically predicted value. The average standard deviation for miscellaneous wastes with COD ranging from 350-57, 050 mg/l was 0.095 ml.

Additional notes concerning this determination are:

1. The standard ferrous ammonium sulfate titrant concentration should be approximately 0.10 N.

2. After refluxing and dilution to a total volume of 140 ml., the samples must be cooled to room temperature before titration.

3. Ferrous ammonium sulfate titrant must be standardized each time it is used.

4. The maximum COD concentration which can be determined using the 20 ml. sample is 1,000 mg/l; for greater COD concentration, lesser volumes of sample diluted to 20 ml. with deionized water should be employed.

Dissolved Oxygen

Dissolved oxygen is measured with a Delta Scientific Company D.O. meter. The meter is standarized periodically against D.O. determined by the Winkler method (S.M., page 406), with the Alkali-Azide Modification.

The meter uses a probe consisting of silver and lead electrodes in a KOH solution and covered by a teflon membrane which will let oxygen pass, but will stop most interfering substances.

Notes:

The instrument cannot be used in the presence of sulfide; however, sulfides are usually present only when D. O. is at zero or close to it.

Nomographs are available to determine true D. O. in the presence of salinity and chlorine.

Sulfates

Sulfate is determined by the tubidimetric method described on page 291 of S.M. It is important in this method to maintain constant conditions of stirring speed and time of stirring throughout the series of analyses in order to insure uniform development of Barium sulfate turbidity. The Bausch & Lomb spectronic 20 is used in this procedure. Cuvets providing a light path of 1 cm. may be used. A new standard transmission curve should be prepared for each set of determinations. The conditioning reagent is designed to reduce pH of the test solution to the acid range when dealing with samples having equivalent buffer capacity of surface and drinking water. If higher concentrations of alkalinity are incurred, prior adjustment of pH with HCL are necessary. The need for such pretreatment can be determined by checking the pH of a sample treated according to the standard method.

Sodium and Potassium

The Coleman model 21 flame photometer with the appropriate filter is used. The maximum expected concentration is set for 100% transmittance and 0 for distilled deionized water. The range is generally 0-50 or 0-100 ppm.

A series of standard solutions are run and the transmittance is subtracted from 100. This value is plotted on the log axis of semilog paper with concentration on the non-log axis. The unknowns are then calculated from this curve.

Chlorides

Total Chloride ion concentration is determined with an Orion combined reference-chloride ion electrode connected to either an Orion specific ion meter or a Beckman Expandometric Potentiometer.

Ten ml. of sample is pipetted into a 50 ml. beaker, 10 ml. of 100 mg/l in 2M K NO_3 is added. The mixture is titrated with $AgNO_3$ added 0.1 ml. at a time. The millivolt reading is plotted vs. ml. $AgNO_3$ added. The inflection point is the end point.

Calculations:

$$\text{Mg/l Cl}^- = \frac{\text{ml AgNO}_3 \times \text{NAgNO}_3 \times 35.45 \times 1000}{\text{ml sample}}$$

Total Dissolved Solids

Total dissolved solids or residue on evaporation is determined according to the method described on page 244 of S.M. Following air drying, the samples are dried at 103°C to constant weight (1+hours).

With ground-water samples there is usually no need to determine th volatile fraction of the residue on evaporation.

With lysimeter leachate, volatile fraction, expressed as weight per volume and percent of total solids, is determined by ashing in the muffle furnace at 600°C for 10 minutes.

The total dissolved solids of the ground-water samples are also determined with a Myron L Dissolved Solids meter, Model 532T1. This instrument measures the conductance of the sample and converts it directly to total dissolved solids.

Hardness

Hardness is determined according to the EDTA titrimetric method described on page 147 of S.M. Since various metal ions interfere with this determination, it is necessary to use an inhibitor in samples of lysimeter leachate. THE INHIBITOR IS SODIUM CYANIDE WHICH IS EXTREMELY DANGEROUS, LIBERATING HYDROGEN CYANIDE UNDER ACID CONDITIONS. The best method of using this inhibitor is to purchase it in packet form from Hach Chemical Company. These packets also contain the buffer solution described in paragraph 2.1.a, page 149 of S.M. and the indicator described in paragraph 2.3.a, page 150 of S.M. In using these packets, attention must be paid to the precautions listed in paragraph 3.1, page 151 of S.M.

Biochemical Oxygen Demand

Biochemical Oxygen Demand (BOD) is a measure of the biodegradable organic content of polluted water. This test, used in conjunction with the COD test, provides a measure of the fraction of total organic matter which is subject to biological degradation. The BOD test is performed in accord with the procedure given on pages 415-421 of S.M. BOD dilution water is prepared with deionized water.

Through experimentation, it has been determined that no seeding of the sample with domestic sewage is necessary to perform the test. The dilution water should be aerated with compressed air at room temperature prior to use. Depending on the estimated value of BOD for a given sample (it can be gained from COD results), the direct pipeting or dilution method is selected for preparing BOD samples. Two methods are available for compensating for any immediate dissolved oxygen demand samples:

1. Aeration of one sample to saturation before preparation BOD dilutions, and

2. Determination of dissolved oxygen remaining in duplicate dilutions 15 minutes after preparation of said dilutions.

Choice of a method is the prerogative of the analyst. BOD is determined periodically (at least once a month) on samples of lysimeter leachate and on ground-water samples drawn from the strata directly beneath the field installation.

All water samples are subjected to routine analysis for COD. This test requires less time than BOD and serves as an indicator of organic contents. Chapter 24 in "Chemistry for Sanitary Engineers"[3] provides an excellent discourse on many practical aspects of the BOD tests. The table of dilutions in this chapter is especially helpful for quickly deciding which three dilutions to prepare for any given sample. After preparation, the BOD samples are incubated for five days at 20°C in the BOD incubator. Dissolved oxygen is then determined by the previously described method.

Phosphate

Phosphate concentration is determined on ground-water samples and lysimeter leachate. The stannous chloride method described on page 234 of S.M. is applicable to the analysis of ground-water samples. A lysimeter leachate sample may contain excessive amounts of organic and inorganic material which will interfere with the stannous chloride method, and hence, the aminonaphtolsulfonic acid method should be used.

This is a difficult analysis to perform and pretreatment of the sample will probably be necessary.

Nitrates

Nitrate analysis is performed on ground-water samples and on lysimeter leachate. Care must be taken in interpreting nitrate analysis results on lysimeter leachate because of the large quantities of dissolved organic and inorganic materials present. The most significant element of this interpretation will be the presence or absence of nitrates (which is an indicator of the presence of aerobic and anaerobic conditions) rather than concentrations measured.

Measurement of ultraviolet absorption at 220 mμ is a valid method of determing nitrate concentration. The nitrate calibration curve follows Beer's law up to concentrations of 11 mg/l NO_3.

Dissolved organic matter may interfere at 220 mμ: however, dissolved organic matter also absorbs at 275 mμ while nitrate does not. This allows a correction for the interference of organic material. The sample must be acidified to prevent interference from hydroxide and/or carbonate ion.

It is necessary to prepare a calibration curve for each set of samples. A series of dilutions ranging from 0 to 0.35 mg N are used. At least five different concentrations and one blank concentration must be run with all samples. A water blank is run between each sample.

Metals

Calcium and Magnesium

Calcium and magnesium contents are determined in the hardness test. Calcium concentration is determined by a modification of the EDTA method which is described on page 74 of S.M. The underlying principle of this modification involves the adjustment of sample pH to a point at which magnesium is precipitated, and hence, only calcium remains in the solution to react with the EDTA titrant. Magnesium concentration is then determined by difference between total hardness and calcium concentration.

Heavy Metals

Analyses for four of the heavy metals (Fe, Cu, Ni, Zn) are performed by using the Beckman Atomic Absorption accessory in combination with a Beckman DB Spectrophotometer,

The samples obtained from the field installation are run directly except 3 ml 1:1 HNO_3 are added to preserve the metals in solution and extremely turbid samples are centrifuged. Samples of leachate from the lysimeter or samples of similar concentrations must first be centrifuged (7500 rpm-10 min) and then, if required, appropriately diluted. Lysimeter leachate is tested full strength for Cu, Ni and Zn, but dilutions of 1:100 must be made for iron determinations.

GAS SAMPLES

Samples from the lysimeter and the field installation are analyzed in the laboratory using the Fisher-Hamilton Gas Partitioner. This instrument contains two columns in series and uses two matched pairs of hot wire filaments. The first column is 6 feet by 1/4 inch diameter. The column contains 30% DEHS on 60-80 mesh chromosorb P. The second column is 6.5 feet by 3/16 inch diameter packed with 40-60 molecular sieve 13x. Gases composed of Nitrogen, Oxygen, Methane, Carbon Monoxide, Carbon Dioxide and Hydrogen Sulfide can be quantitatively analyzed with this system. The first column separates CO_2 from the remaining components which remain lumped together as the first composite peak, while the second column separates the remainder of the gases. The observed retention times of the different gases are listed below, along with specified experimental conditions:

Retention Times of Landfill Gases

Gas	Retention Time in Minutes
CO_2	1.75
O_2	2.75
N_2	3.75
H_2S	4.75
CH_4	5.25
CO	7.00

Flow rate of Helium is 40 ml/min.
Milliamps - 240.

Sampling Procedure

The types of sample containers used for the gas samples appear in the following figure:

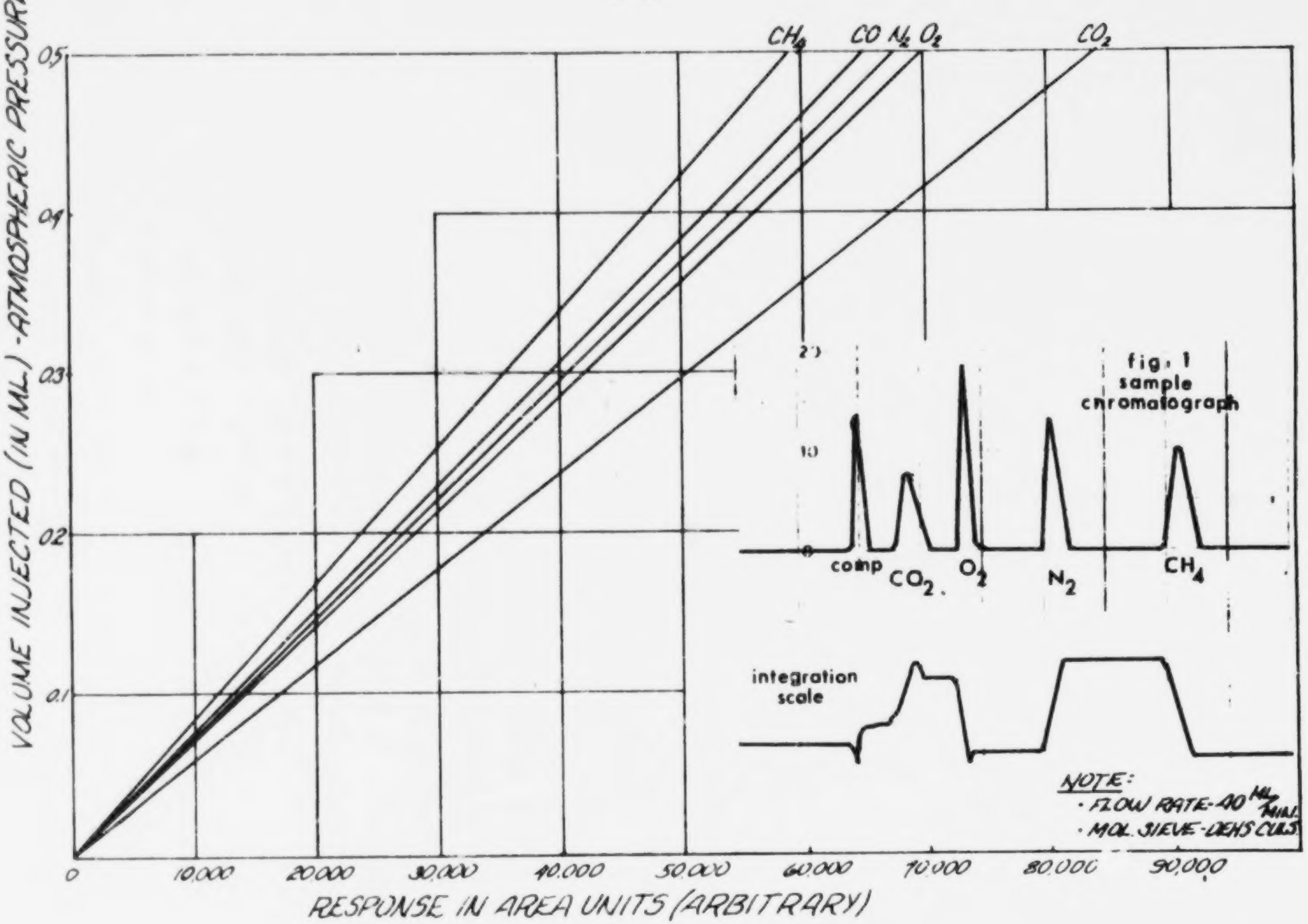
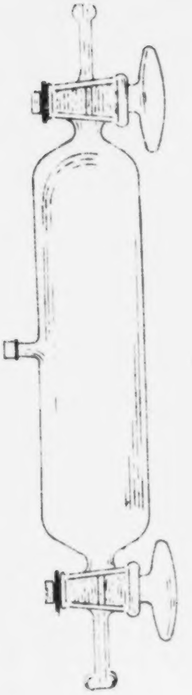


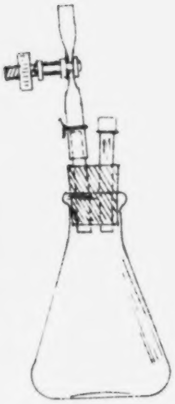
fig. 1 sample chromatograph

INJECTED VOLUME vs. AREA RESPONSE
FISCHER-HAMILTON PARTITIONER WITH SPEEDOMAX H RECORDER

fig. 2



A



B

While the commercially available gas sampling bulb, A, was used in the initial stages of this investigation, it was found that a gas sampling tube, designed and constructed in our laboratory, served just as well. Because of its inexpensive construction, this gas sampling tube, B, could be mass-produced and permitted a large number of samples to be run during a given day without re-evacuation. The sampling procedure involved first the evacuation of the tube, either type A or B, by means of a high vacuum pump. In the case of A, one stop-cock is kept closed and the other opened to the vacuum end of the pump with the rubber septum kept on. To evacuate B, the right-hand fitting is connected by means of the rubber terminus to a glass fitting at the end of the vacuum pump, the pinch clamp is opened and a vacuum is established. After about 10-15 minutes, either the open stop-cock in the case of type A or the pinch clamp in type B is closed. A system which permits evacuation of a large number of sampling bulbs has been constructed.

Sample Collection Procedure

1. The suction end of a pressure suction type rubber sampling bulb is connected to a sampling hose.

2. The sample hose is purged a sufficient number of times to remove the volume of gas in the hose.

3. The evacuated sampling tube is then connected to the pressure end of the rubber bulb.

4. After connecting the stop-cock, the sampling tube is opened, and the vacuum draws the sample into the tube.

5. The stop-cock is then closed, and the tube is ready to be returned to the laboratory.

6. In the laboratory, the gas sample is analyzed with a gas chromatograph.

A detailed operating procedure for this equipment is given in Appendix D.

SOLID SAMPLES

The chemical composition of raw refuse is determined by using the standard methods described in "Municipal Refuse Disposal".[6] All samples are ground by means of a hammermill to one square inch to promote homogeneity. Aliquots of this ground refuse are then analyzed for:

1. Crude fiber content.
2. Moisture content.
3. Ash.
4. Volatile percentage.
5. Carbon.
6. Nitrogen.
7. Total water soluble solids.
8. Water solubles:
    - a) sodium
    - b) chloride
    - c) nitrogen
    - d) phosphate
    - e) sulfate
    - f) COD

The analyses for the water soluble pollutants are described in the liquid sample section of this manual. The water samples are prepared by digesting a known quantity of ground refuse in a known volume of water for 24 hours. The remaining refuse is dried and weighed to determine the water-soluble portion. Using this data, a conversion factor is developed to convert the analytical results of mg/l to the more representative units of mg pollutant per gram of dry refuse. The non-combustible fraction of the raw refuse is analyzed by emission spectroscopy to obtain a semiquantitative estimate of the constituents of that fraction.

APPENDIX A

pH and Alkalinity

1. Check pH meter before doing:

    a. Temperature compensation - check sample temp.

    b. Millivolts - both buttons up.

    c. Refill the Orion single junction daily.

    d. Wash off electrodes with distilled H_2O. Dry electrodes.

    e. Insert electrodes in buffer solution - pH 7.

    f. Depress electrode "read" button and after a few minutes, adjust meter needle to 7.0 using "Standardize" dial.

    g. Repeat process with pH 4.0 buffer.

    h. Depress "standby" button, remove electrodes from buffer; wash with distilled H_2O.

2. Measure out a 100 ml. sample (or larger volume) using graduated cylinder. Transfer into 150 or 250 ml. beaker being careful not to agitate the sample.

    For samples high in alkalinity, a 10 ml. sample is measured for pH and then diluted to a final volume for alkalinity titration.

3. Insert electrodes in sample beaker. Do not allow electrodes to touch the bottom of beaker. Rotate beaker slowly to insure proper mixing of sample.

4. Depress "read" button and measure pH.

5. Depress "standby" button; remove electrodes; insert stirrer bar; turn stirrer control to approximately 5.

6. Reinsert electrodes being careful not to let stirrer bar strike them.

7. Depress pH button and titrate sample to appropriate endpoint pH with 1 appropriate strength H_2SO_4 (sulfuric acid). Record volume of acid used.

8. Depress "standby" button; turn stirrer off; remove electrodes from sample; wash electrodes with distilled H_2O; insert in distilled H_2O or next sample. Remove stirrer bar from sample.

9. Never allow the pH switch to be depressed when electrodes are not submerged in a solution (either distilled water or sample).

APPENDIX B

Suspended Solids Determination - Glass Fiber Filters

Taring of Filter Pads

1. Check the zero of the Mettler Balance.

2. Weigh the filter pads and place the weighed pad in an evaporation dish for carrying. Handle the pads with tweezers, never with the fingers.

3. Record weights under tare column and opposite the dish number.

Filtering the Sample

1. Check cleanliness of filtering apparatus.

2. Place the filter pad on the fitted glass filter holder, using tweezers, and clamp the upper portion of the filtering assembly in place.

3. Run the blank filters first. Use volume of distilled water equal to largest sample for the blank. Filter, remove with spatula, and place pad in evaporating dish.

4. Filter the rest of the samples using volumes as directed. Be sure to shake sample thoroughly before pipeting filter volume. Use open-tip pipet for transferring same to the filter assembly.

5. After sample is completely filtered and no liquid remains on pad, wash down sides of filter assembly with a small amount of distilled water from squeeze bottle.

6. When filter pad is again "dry" turn off vacuum and place pad in evaporating dish. Check rim of filter assembly for solids residue and, if present, transfer as well as possible to pad.

Drying and Weighing

1. Place evaporating dishes containing filter pads in 103°C oven for one hour.

2. Remove from oven, cool in desiccator for 20 minutes and weigh on Mettler Balance. Record weights.

3. Ignite pads in dishes in the muffle furnace for 10 minutes. Remove, cool in air for 15 minutes and weigh on Mettler Balance. Record weights.

APPENDIX B (Cont'd.)

Calculations

Total Solids: $\left[\underset{\text{Sample}}{(\text{Dry Wt.} - \text{Tare})} + \underset{\text{Blank}}{(\text{Tare} - \text{Dry Wt.})}\right] 10^3 \times \frac{10^3}{\text{Sam. Vol.}}$

Volatile Solids: $\left[\underset{\text{Sample}}{(\text{Dry Wt.} - \text{Ign. Wgt.})} - \underset{\text{Blank}}{(\text{Dry Wt.} - \text{Ign. Wgt.})}\right] 10^3 \times \frac{10^3}{\text{Sam. Vol.}}$

% Volatile = $\frac{\text{Volatile Sol.}}{\text{Total Sol.}} \times 100$

APPENDIX C

Nitrogen - Kjeldahl

Ammonia

1. Measure out a 375 ml. sample in a 500 ml. graduated cylinder and transfer it to a beaker. Adjust the pH to 7.0 and transfer to Kjeldahl flask. Wash out cylinder by filling it with distilled water and adding the water to the Kjeldahl flask.

2. Add 25 ml. of phosphate buffer to the Kjeldahl flask containing the sample.

3. Distill over the ammonia.
   a. Turn on condenser water valve of Kjeldahl apparatus.
   b. Add 4 or 5 glass beads to each Kjeldahl flask before placing on apparatus.
   c. Place flasks on heaters and turn heater controls on.
   d. Insert collector tips into collecting beakers containing 50 ml. of boric acid solution.

4. Distill liquid over until beaker is filled to the mark (250 ml.). Turn heaters off and remove collection tips from solution.

5. Determine Nitrogen content by titration to pH of 4.5 or green indicator endpoint with 0.02 N H_2SO_4.
   *(If NH_3-N content is < 5 mg/l, collect distillate without boric acid solution and determine NH_3-N by nesslerization.

Organic Nitrogen

1. Add one $HgCl_2$ catalyst tablet and 10 ml. conc. H_2SO_4 to each of the Kjeldahl flasks used in the ammonia determination.

2. Place the flasks in position on the lower portion of the Kjeldahl apparatus.

3. Turn on the blower and the heating units.

4. Allow samples to "digest" for 30 minutes after the samples have cleared of white fumes (this clearing will take about one hour).

5. After above time has elapsed, turn off heaters leaving blower on. Allow flasks to cool.

6. Remove flasks from apparatus and add 300 ml. of distilled water to each flask.

7. Add 50 ml. of "organic nitrogen sodium hydroxide solution" to each flask.

8. Distill and analyze as with ammonia nitrogen.

APPENDIX D

Operating Procedure for the Fisher-Hamilton Gas Partitioner Model 297

1. Turn the cell power switch to the on position. Note: the cell power switch should never be turned on unless the carrier gas is flowing. If the carrier gas flow is interrupted, always turn the cell power switch to off.

2. Adjust the flow control valve until the desired flow rate is established. Forty ml/min is suggested as an optimum rate for use.

   The flow rate may be checked with the bubble tower, as explained in the instruction manual.

3. The partitioner must be in thermal equilibrium before any analysis can be performed. At least six hours is required for the Model 29 to reach equilibrium; therefore, the cell power switch will be kept in the on position and the carrier gas flowing at a rate of at least 4 ml/min at all times.

4. Zeroing the Recorder: to zero the Speedomax W recorder with Disc Integrator, the Attenuate control should be turned to the SHORT position. This shorts the recorder leads, and the indicator should now rest at zero position.

5. Balance the partitioner by turning the Attenuate control to 1. Then, by using the coarse and fine balance controls on the partitioner, again bring the recorder pen to the zero baseline.

6. Sample Deliver: a) Using a 1-ml. Hamilton Syringe (Fisher Catalog No. 14-820-10) with a Chaney Adapter, remove a 1 ml. sample from the Erlenmeyer flask sampling devices, mentioned previously. This is done by inserting the needle through the septum cap on the flask and then flushing the syringe once or twice with the sample before removing the needle; b) insert the syringe needle through the diaphragm of the sample injection part and rapidly depress the plunger; c) set Attenuate switch to 8. If peaks are off, scale change Attenuation until each peak is on the scale. The right attenuation for each gas will vary with sample,and experience will indicate the proper attenuation for different concentrations.

7. Calculation of Peak Areas: A sample chromatogram of the landfill gases is shown in Figure 1. The integrating scale is indicated on the bottom of this graph. To determine the area of the peaks for each gas, the number of lines crossed by the indicator is then multiplied by the attenuation.

APPENDIX D (Cont'd.)

8. Calculation of Percentage Composition: Absolute concentrations are not determined -- only relative concentrations in % by volume. These are determined by measuring the peak areas. Substitution of the peak areas in equations (1) would give the % volumes for components A, B, C, ...

$$\% \text{ Volume A} = \frac{\text{area A}}{\text{area}_A + \text{area}_B + \text{area}_C + \ldots} \times 100 \qquad (1a)$$

$$\% \text{ Volume B} = \frac{\text{area B}}{\text{area}_A + \text{area}_B + \text{area}_C + \ldots} \times 100 \qquad (1b)$$

$$\% \text{ Volume C} = \frac{\text{area C}}{\text{area}_A + \text{area}_B + \text{area}_C + \ldots} \times 100 \qquad (1c)$$

etc.

Now, this set of equations is not exact in that it has tacitly assumed an equal response on the gas chromatographic detector for equal volumes of each of the component substances. While this is approximately true, it is not exact as we have shown.

To correct this lack of identity of response, response factors in peak area/ml. gas injected or the reciprocals were determined. These factors are inserted as correction factors to give the following equations:

$$\text{Corrected } \% \text{ Volume A} = \frac{\text{area A}/K_A}{\text{area A}/K_A + \text{area B}/K_B + \text{area C}/K_C + \ldots} \times 100 \qquad (2a)$$

$$\text{Corrected } \% \text{ Volume B} = \frac{\text{area B}/K_B}{\text{area A}/K_A + \text{area B}/K_B + \text{area C}/K_C + \ldots} \times 100 \qquad (2b)$$

$$\text{Corrected } \% \text{ Volume C} = \frac{\text{area C}/K_C}{\text{area A}/K_A + \text{area B}/K_B + \text{area C}/K_C + \ldots} \times 100 \qquad (2c)$$

K_A, K_B, K_C, ... are the reciprocals for the response factors in ml. gas injected/peak areas. These are listed on the next page.

APPENDIX D (Cont'd.)

Reciprocals for Response Factors for Various Landfill Gases

Gas	Reciprocal of response factor, K, in $\frac{\text{ml. gas injected}}{\text{peak area (arbitrary units)}}$
O_2	7.05
N_2	7.44
CO_2	5.99
CH_4	8.43
CO	7.66

It is clear that the constants are somewhat variable. The data used for the determination of these constants are plotted in Figure 2. In order to obtain these plots, various volumes of pure gas at atmospheric pressure were injected into the gas chromatograph and the resulting peak areas measured.

Gases of purity greater than 99% were used in all cases. The slopes of the best straight lines in each case give the respective reciprocals of the response factors in ml. gas injected/unit area x 10^6.

APPENDIX E

Detailed Procedure of Heavy Metal Determinations

Once the atomic absorption unit and the Beckman DB spectrophotometer have been turned on and properly adjusted, it is necessary to produce a standard curve using a serial dilution of the metal of interest. This curve is used to determine the metal concentrations in samples. If it is necessary to drastically alter some control, such as the fuel or slip opening, then a new set of standards must be run and a new curve obtained for that setting. It is absolutely necessary that a standard curve be made each time the apparatus is started after being shut down.

The standard concentration series is made from a dilution of a stock solution of 200 mg/l. It has been found that concentrations of 0.3, .6, .9, 1.2 and 1.5 mg/l are acceptable for making standard curves for Cu, Fe and Ni. These three metals can be combined in one set of standards. It is necessary to make a separate series of standards for Zn. The concentrations should range from 0.05 to .7 mg/l. The three metals, Fe, Cu and Ni, are run in the same manner.

Operating procedures for the Beckman DB Spectrophotometer with atomic absorption accessory are best obtained from their respective manuals.

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1. Standard Methods for the Examination of Water and Wastewater. Twelfth edition. New York: American Public Health Association, Inc., 1965.

2. A. W. Lawrence [Private Communication].

3. Sawyer, C. N. and McCarty, P. L., Chemistry for Sanitary Engineers. McGraw Hill Book Company, New York, 1967.

4. Wyckoff, B. M., "Rapid Solids Determination Using Glass Fiber Filters," Water and Sewage Works, 111, No. 6: 277-80, 1964.

5. Smith, A. L., and A. E. Greenberg, "Evaluation of Methods for Determing Suspended Solids in Wastewater," Journal Water Pollution Control Federation, 35: 940-43, 1963.

6. Municipal Refuse Disposal. Chicago: American Public Works Assoc., 1966.

7. Fisher Scientific. Fisher/Hamilton Gas Partitioner Instruction Manual.

APPENDIX 2

Photographs of Laboratory Sanitary Landfill Lysimeter

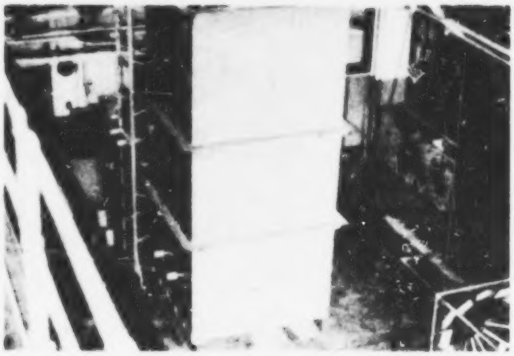

PHOTO 1

LYSIMETER PRIOR TO INSTRUMENTATION

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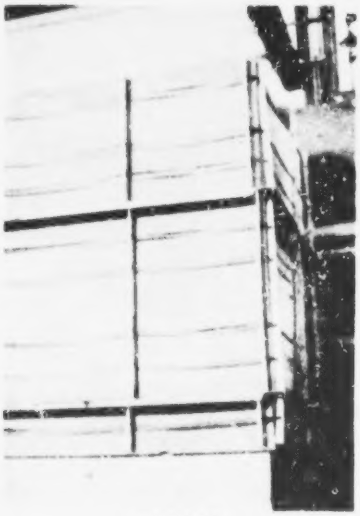

PHOTO 2

INSTALLATION OF HEATING TAPES

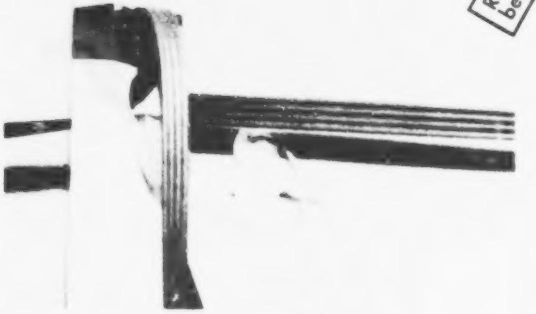

PHOTO 3

INSTALLATION OF THERMISTORS FOR CONTROLLING AND MONITORING OF HEATING TAPES

PHOTO 4

LEACHATE COLLECTION TROUGH WITH FIBERGLASS LINING

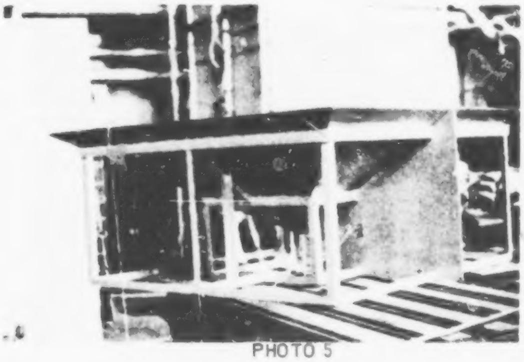

PHOTO 5

STRUCTURAL SUPPORT FOR LEACHATE COLLECTION TROUGH

PHOTO 6

LOADING OF PREPARED REFUSE IN COMPACTION BOX

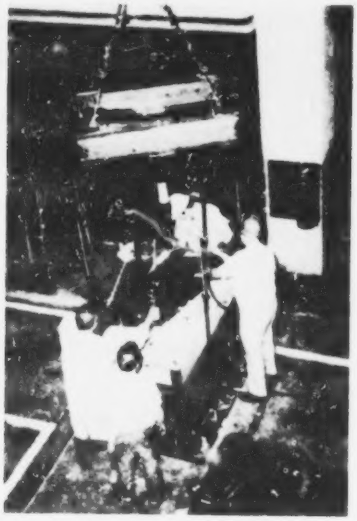

PHOTO 7

POSITIONING OF COMPACTION JACK

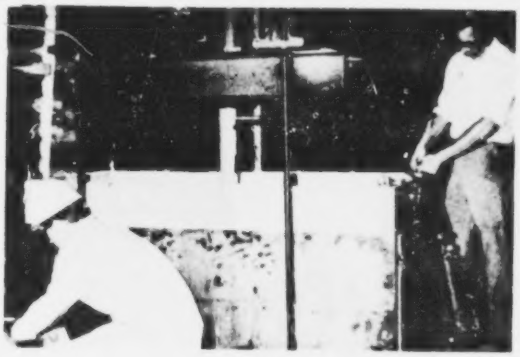

PHOTO 8

COMPACTION JACK IN POSITION

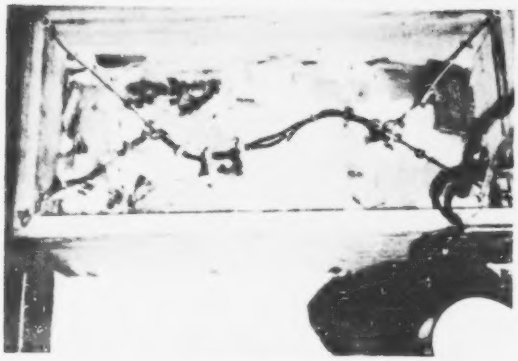

PHOTO 9

EMPLACEMENT OF COMPACTED REFUSE IN LYSIMETER

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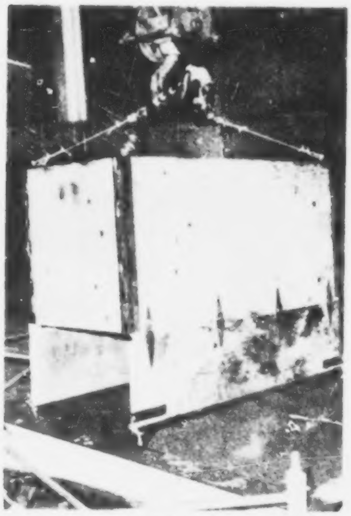

PHOTO 10

LOADING BOX WITH BOTTOM DOORS OPEN

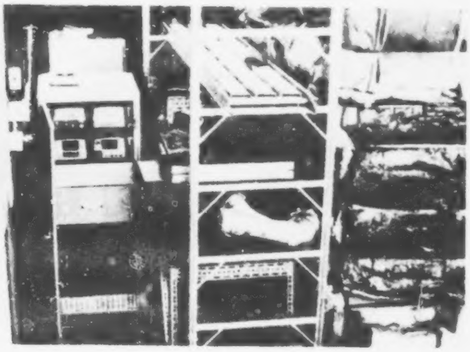

PHOTO 11

THERMISTOR AUTOMATIC SCANNING-PRINTING SYSTEM

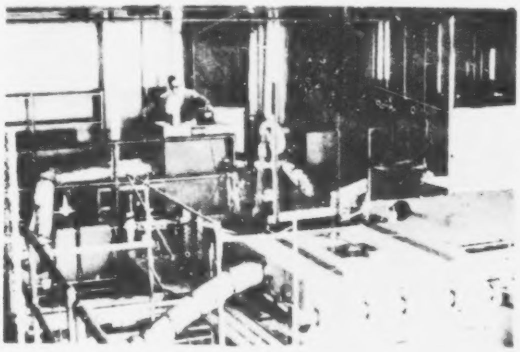

PHOTO 12

TOP OF LYSIMETER

APPENDIX 3

Photographs of Field Experimental Sanitary Landfill

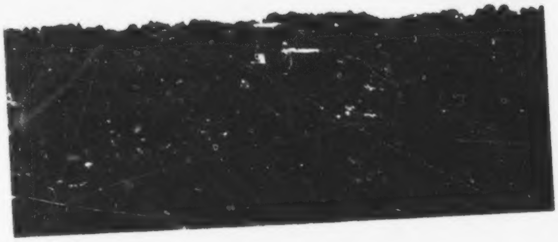

Fig. 1 – Initial Condition of Test Site.

Fig. 2 – Excavation for Test Landfill.

Fig. 3 – Four Ft. Diameter Caisson in In-situ Soil Below Test Landfill Excavation.

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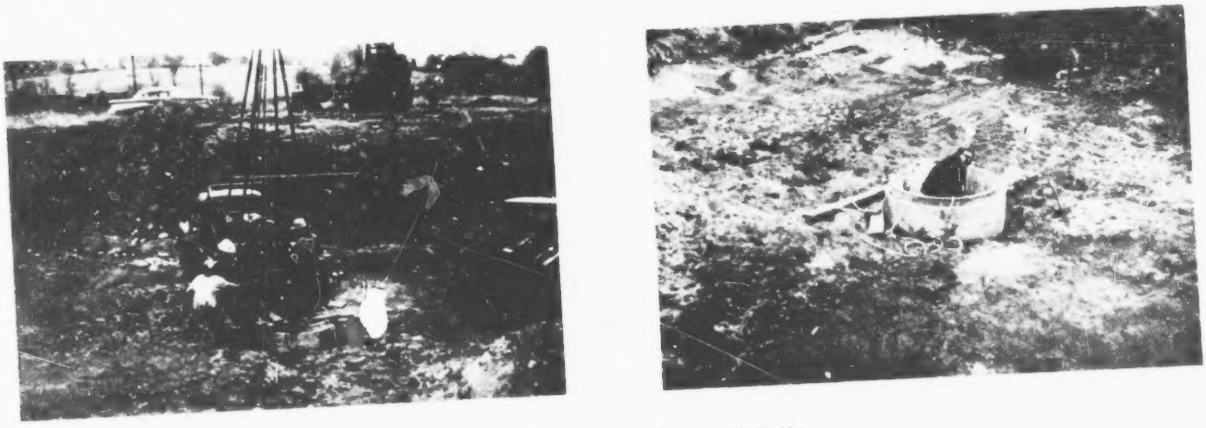
Fig. 4 – Sections of Four Ft. Diameter Caisson Within Test Landfill Excavation.



Figs. 5-6 – Installation of Gas Sample Wells.

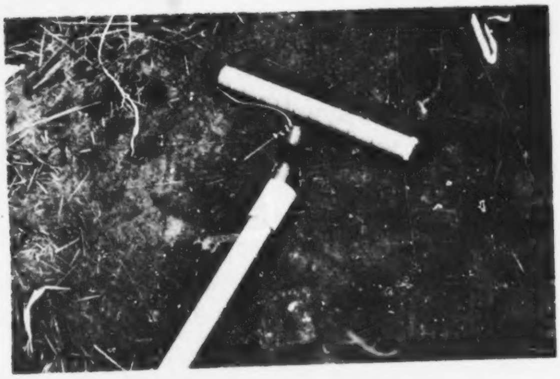


Fig. 7 – Gas Sample Pipe and Thermistor Probe Prior to Sealing.

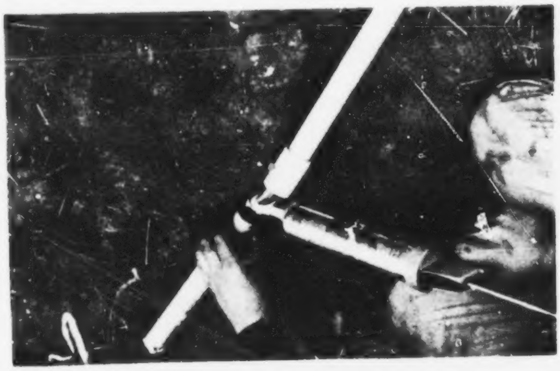


Fig. 8 – Sealing Pipe with Silicone Sealant.

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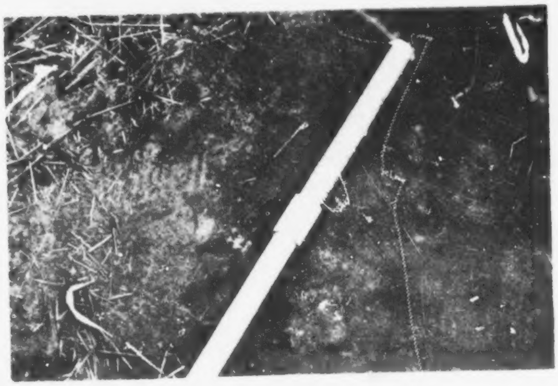


Fig. 9 – Gas Sample Pipe and Thermistor Probe Ready for Installation.

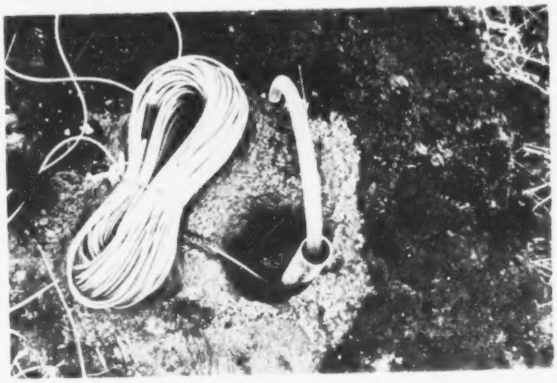


Fig. 10 – Gas Sample Pipe and Thermistor in Place.

Fig. 11 – Backfilling of Pipe.

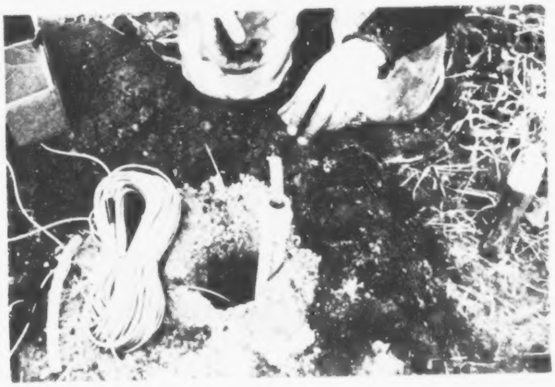
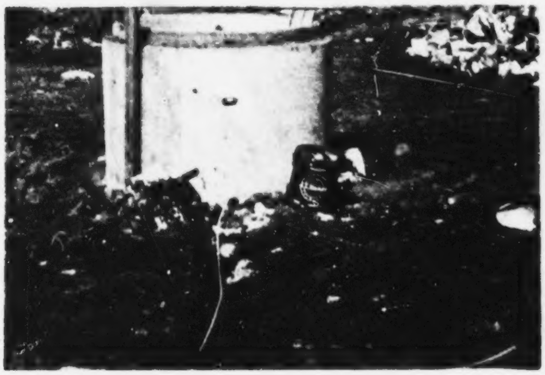


Fig. 12 – Capping Pipe.



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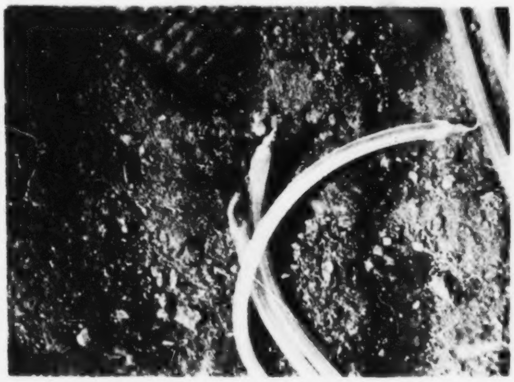

Fig. 13 – Concrete Caisson with Laterals Located Six Feet Below Top of Landfill.

Fig. 14 – Typical Gas Sample Laterals.

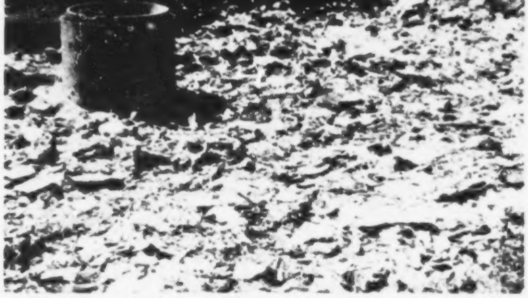

Fig. 15 – Compaction of Refuse.

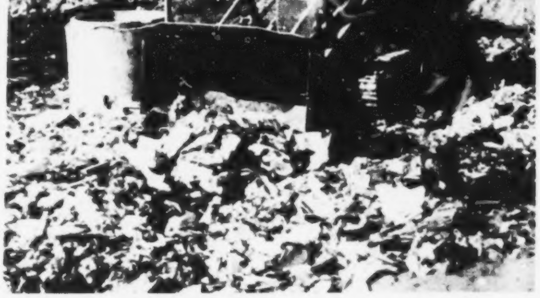

Fig. 16 – Compacted Refuse Prior to Daily Six Inch Soil Cover.

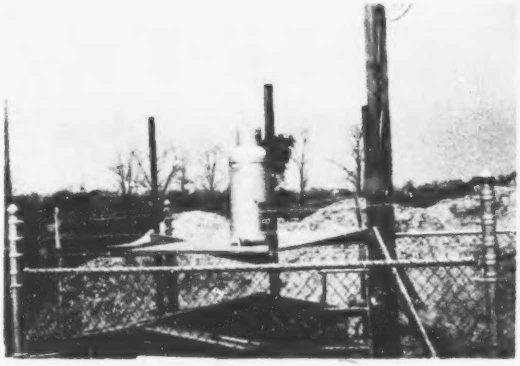

Fig. 17 – Strip Chart Rain Gauge.

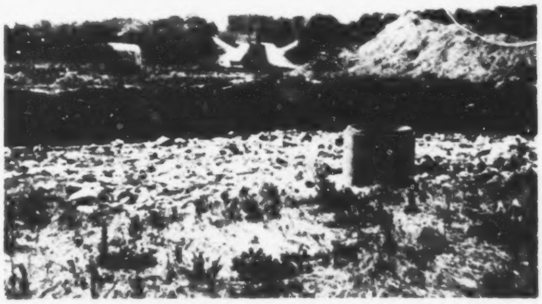

Fig. 18 – Landfill nearing Completion.

APPENDIX 4

Outline of Procedure for Using The Nuclear Chicago Model P19 Subsurface Soil Moisture Probe and the Model P20 Depth Density Probe

The Model P19 Subsurface Soil Moisture Probe contains a radiation source which produces fast neutrons and a detector which is only sensitive to slow neutrons. As the fast neutrons travel through the soil, they are slowed by hydrogen atoms and become "slow neutrons." These are then counted by the detector. Therefore, with a known rate of emitting fast neutrons, the number of slow neutrons detected per unit of time can be related to moisture content.

The Model P20 Depth Density Probe contains a gamma source separated from a gamma detector by a shield. This detector receives only those gamma rays which have been transmitted to the surrounding soil and have been reflected back toward the detector. Since a higher percentage of the reflected gamma rays are absorbed by denser material, the count rate is inversely proportional to the density of the material.

The operating procedure for both probes is primarily identical and very simple. Both units are used in conjunction with the Model 5920 d/M Gauge scaler. The procedure is as follows:

1. The probe is connected to the input of the scaler.
2. The scaler voltage is set to the appropriate value.
3. A standard count is taken as described in the unit operations manuals.
4. The probe is lowered to the desired depth in the access tube.
5. A one-minute count is taken on the scaler.
6. The count is then converted to the appropriate units using calibration charts supplied by the manufacturer.
7. The probe is lowered to a new depth for a new count.

APPENDIX 5

A Computer Program for Moisture Routing Through an Unsaturated Sanitary Landfill

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INTRODUCTION

One variable which influences the quality and quantity of leachate generated by a sanitary landfill is the quantity of infiltration water. This program is for routing infiltration water through an unsaturated sanitary landfill in order to determine parameter influence on the appearance and quantity of leachate.

The system considered is a one-dimensional vertical flow through system containing a refuse layer covered by soil. The cover soil is made up of an active layer, susceptible to environmental conditions, and a passive layer not affected by environmental conditions.

The basic equation satisfied is the equation of continuity.

$$\Delta\theta = Q_I - Q_O$$

where

$\Delta\theta$ = change in water stored in a layer

Q_I = water flow into a layer

Q_O = water flow out of the layer

The passive soil layer and the refuse will monotonically store water until their respective field capacities are reached. Thereafter they will maintain their field capacity and pass any excess water as long as they are free to do so. Their field capacities and other physical properties are determined and utilized as discussed in reference 1.

The active soil layer is affected by environmental conditions and water accumulation and pass-through are complex. Briefly, the amount of water which passes through depends on evapotranspiration, surface vegetation and related factors (1).

The program for routing the soil-refuse system is divided into three sections (Figure 1):

1) Moisture through the active soil layer
2) Moisture through the passive soil layer
3) Moisture through the refuse

The program is written in Fortran II for use on an IBM 360/65

Input

(Units and Symbols are presented in Table I)

Program input includes:

a) Water added monthly at the active layer's free surface
b) Number of systems to be evaluated
c) Physical parameters of the active soil layer
    1. Field capacity
    2. Wilting percentage
    3. Original moisture content
    4. Thickness of layer
d) Physical parameters of the passive soil layer
    1. Field capacity
    2. Wilting percentage
    3. Original moisture content
    4. Thickness of layer
e) Physical parameters of the refuse
    1. Field capacity
    2. Original moisture content
    3. Thickness of layer
f) Total thickness of refuse lift
g) Date of starting month

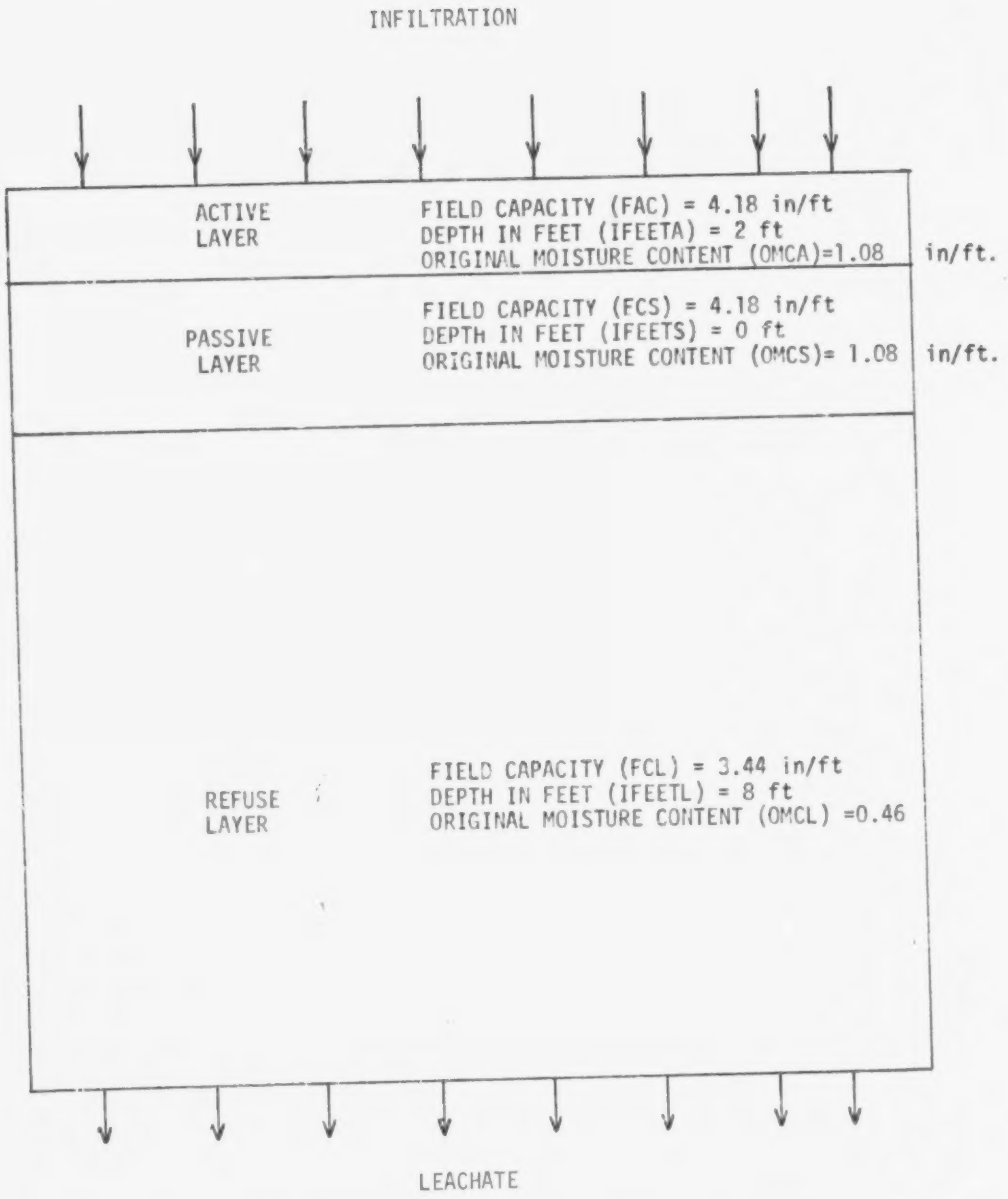
INFILTRATION
ACTIVE LAYER
FIELD CAPACITY (FAC) = 4.18 in/ft
DEPTH IN FEET (IFEETA) = 2 ft
ORIGINAL MOISTURE CONTENT (OMCA)=1.08 in/ft.
PASSIVE LAYER
FIELD CAPACITY (FCS) = 4.18 in/ft
DEPTH IN FEET (IFEETS) = 0 ft
ORIGINAL MOISTURE CONTENT (OMCS)= 1.08 in/ft.
REFUSE LAYER
FIELD CAPACITY (FCL) = 3.44 in/ft
DEPTH IN FEET (IFEETL) = 8 ft
ORIGINAL MOISTURE CONTENT (OMCL) =0.46
LEACHATE

FIG. 1 - LAYER DEFINITIONS AND SAMPLE PROBLEM PARAMETERS

Output

Program output includes:

a) Listing of input parameters

b) Elapsed time necessary to bring each layer to field capacity

c) Moisture surplus for addition to the next underlying layer

d) Monthly leachate production

COMPUTER PROGRAM

TABLE I - SYMBOLS & UNITS FOR PROGRAM

FAC=Field Capacity of Active Layer in Inches/Foot

FCL=Field Capacity of Landfill in Inches/Foot

FCS=Field Capacity of Passive Soil Layer in Inches/Foot

IFEETA=Total Thickness of Active Layer in Feet

IFEETL=Thickness of Landfill in Feet

IFEETS=Total Thickness of Passive Soil Layer in Feet

JWATR=The Month, The Beginning of which the Landfill is Placed (For July, JWATR=07)

OMCA=Original Moisture Content of Active Layer in Inches/Foot

OMCL=Original Moisture Content of Landfill in Inches/Foot

OMCS=Original Moisture Content of Passive Soil Layer in Inches/Foot

STORAC(L)=Amount of water in Active Soil Layer at a Specified Time in Inches/Foot

STORLF(I)=Amount of Water in Landfill Layer at a Specified Time in Inches/Foot

STORPA(I)=Amount of Water in Passive Soil Layer at a Specified Time in Inches/Foot

TLAYER=Thickness of Layer being Evaluated in Feet

WATER(I)=Monthly Amount of Water Input at Surface in Inches

WILT=Wilting Moisture of Active Layer in Inches/Foot

TABLE 2 - PLACEMENT OF DATA CARDS

1. Monthly water input at surface, one set per card, in a field of width 6 and decimal 2 in chronological order. Example problem #1-Jan., Feb., March, then problem #2-Jan., Feb., March, etc. A trailer card of +99.99 is used to terminate the rainfall data.

2. One data card carrying the integer of the number of problems in integer field of width 3.

3. One card with FCA, OMCA, WILT, IFEETA in three real fields of 6.2 and one integer field of 3. Followed immediately by FCS, OMCS, IFEETS in two real fields of 6.2 and one integrer field of 3. Followed immediately by FCL, OMCL, IFEETL in two real fields of 6.2 and one integer of 3. Followed by TLAYER, JWATR in one real field of 9.5 and one integer field of 3. This step is repeated in the correct order for each additional set of problem data.

COMPUTER PROGRAM

TABLE I - SYMBOLS & UNITS FOR PROGRAM

FAC=Field Capacity of Active Layer in Inches/Foot

FCL=Field Capacity of Landfill in Inches/Foot

FCS=Field Capacity of Passive Soil Layer in Inches/Foot

IFEETA=Total Thickness of Active Layer in Feet

IFEETL=Thickness of Landfill in Feet

IFEETS=Total Thickness of Passive Soil Layer in Feet

JWATR=The Month, The Beginning of which the Landfill is Placed (For July, JWATR=07)

OMCA=Original Moisture Content of Active Layer in Inches/Foot

OMCL=Original Moisture Content of Landfill in Inches/Foot

OMCS=Original Moisture Content of Passive Soil Layer in Inches/Foot

STORAC(L)=Amount of water in Active Soil Layer at a Specified Time in Inches/Foot

STORLF(I)=Amount of Water in Landfill Layer at a Specified Time in Inches/Foot

STORPA(I)=Amount of Water in Passive Soil Layer at a Specified Time in Inches/Foot

TLAYER=Thickness of Layer being Evaluated in Feet

WATER(I)=Monthly Amount of Water Input at Surface in Inches

WILT=Wilting Moisture of Active Layer in Inches/Foot

```
C LANDFILL III- WATER ROUTING IN A SANITARY LANDFILL
      DIMENSION WATER(500),STORAC(1000),STORPA(1000),STORLF(1000)
      DIMENSION ITIMA(1000)
      DO 103 I=1,500
  101 READ(5,104)WATER(I)
  104 FORMAT(F6.2)
      LIMIT=I
      IF(WATER(I)-99.99)103,100,103
  100 LIMIT=LIMIT-1
      GO TO 102
  103 CONTINUE
  102 READ(5,105)NOPROB
  105 FORMAT(I3)
      WRITE(6,106)NOPROB
  106 FORMAT(///,5X,'ALTOGETHER,'I3,' PROBLEMS ARE EMBRACED IN THIS PART
     1ICULAR RUN')
  200 DO 300 J=1,NOPROB
  201 FORMAT(2F6.2,I3)
  202 FORMAT(3F6.2,I3)
      READ(5,202)FCA,OMCA,WILT,IFEETA
  203 FORMAT(1H1,5X,'ACTIVE SOIL COVER CHARACTERISTICS')
      WRITE(6,203)
  204 FORMAT(5X,'FIELD CAPACITY=',F6.2,'  ORIGINAL MOISTURE CONTENT=',F6
     1.2,'  THICKNESS=',I3,' FEET')
      WRITE(6,204)FCA,OMCA,IFEETA
  205 FORMAT(5X,'SOIL WILTING MOISTURE=',F6.2)
      WRITE(6,205)WILT
      READ(5,201)FCS,OMCS,IFEETS
  206 FORMAT(/,5X,'PASSIVE SOIL CHARACTERISTICS')
      WRITE(6,206)
      WRITE(6,204)FCS,OMCS,IFEETS
      READ(5,201)FCL,OMCL,IFEETL
  207 FORMAT(/,5X,'LANDFILL CHARACTERISTICS')
      WRITE(6,207)
      WRITE(6,204)FCL,OMCL,IFEETL
  208 FORMAT(F9.5,I3)
      READ(5,208)TLAYER,JWATR
  209 FORMAT(//,5X,'IN THIS PROBLEM NO.',I3,', LAYERS ARE TAKEN TO BE',F
     19.5,' FEET THICK FOR COMPUTATIONS')
      WRITE(6,209)J,TLAYER
  250 FORMAT(/,5X,'THIS COMPUTATION ASSUMES THAT THE MATERIAL IS PLACED
     1AT THE BEGINNING OF MONTH',I3)
      WRITE(6,250)JWATR
      FCA=TLAYER*FCA
      OMCA=TLAYER*OMCA
      WILT=TLAYER*WILT
      FCS=TLAYER*FCS
      OMCS=TLAYER*OMCS
      FCL=TLAYER*FCL
      OMCL=TLAYER*OMCL
      FEETA=IFEETA
      IFEETA=FEETA/TLAYER
      FEETS=IFEETS
      IFEETS=FEETS/TLAYER
      FEETL=IFEETL
      IFEETL=FEETL/TLAYER
      DO 210 I=1,IFEETA
      STORAC(I)=OMCA
  210 ITIMA(I)=1
      IF(IFEETS)248,249,248
  248 DO 211 I=1,IFEETS
  211 STORPA(I)=OMCS
  249 DO 212 I=1,IFEETL
  212 STORLF(I)=OMCL
  213 FORMAT(//,7X,'ACTIVE',/,5X,'SOIL COVER',5X,'ELAPSED TIME',29X,'MON
     1THLY INFILTRATION',/,5X,'LAYER NO.',4X,'YEARS   MONTHS',5X,'SURPLU
     2S FOR LAYER',9X,'IN INCHES')
      WRITE(6,213)
      ITIME=1
      INDIC=1
      NEGIND=1
      LAYAC=1
      LAYPA=1
      LAYLF=1
      JWATR=JWATR-1
      JJWAT=JWATR
   10 JWATR=JWATR+1
      IF(JWATR-LIMIT)216,216,214
  214 LIMIT=LIMIT-JJWAT
      WRITE(6,215)LIMIT,J
  215 FORMAT(/,5X,'END OF',I3,' MONTHS FOR PROBLEM',I3)
      LIMIT=LIMIT+JJWAT
      GO TO 300
  216 WRITE(6,217)WATER(JWATR)
  217 FORMAT(66X,F6.2)
      IF(WATER(JWATR))222,218,218
  218 IF(ITIME-1)219,220,219
  219 ADDWAT=WATER(JWATR)
   13 GO TO (12,20,21,22),INDIC
  220 IF(NEGIND)221,12,12
  221 NEGIND=1
      GO TO 223
  222 NEGIND=-1
  223 LAYAC=1
      ITIME=1
   12 ADDWAT=WATER(JWATR)
   11 STORAC(LAYAC)=STORAC(LAYAC)+ADDWAT
      IF(STORAC(LAYAC)-WILT)224,226,226
  224 IF(WATER(JWATR))225,10,10
  225 IF(ITIMA(LAYAC)-1)262,260,262
  260 IF(OMCA-WILT)261,262,262
  261 ADDWAT=STORAC(LAYAC)-OMCA
      STORAC(LAYAC)=OMCA
      GO TO 263
  262 ADDWAT=STORAC(LAYAC)-WILT
      STORAC(LAYAC)=WILT
  263 LAYAC=LAYAC+1
      IF(LAYAC-IFEETA)11,11,10
  226 IF(STORAC(LAYAC)-FCA)10,227,227
  227 ADDWAT=STORAC(LAYAC)-FCA
      STORAC(LAYAC)=FCA
      IF(ITIMA(LAYAC)-1)228,231,228
  228 IF(LAYAC-IFEETA)230,229,230
  229 ITIME=2
      GO TO 13
  230 LAYAC=LAYAC+1
```

```
      GO TO 11
  231 CALL TIMER(MONTH,LYEAR,JWATR,JJWAT)
      ITIMA(LAYAC)=2
      WRITE(6,232)LAYAC,LYEAR,MONTH,ADDWAT
  232 FORMAT(7X,I3,8X,I3,6X,I3,12X,F6.2)
      IF(LAYAC-IFEETA)233,234,234
  233 LAYAC=LAYAC+1
      GO TO 11
  234 IF(IFEETS)237,235,237
  235 INDIC=3
  236 FORMAT(//,6X,'LANDFILL',6X,'ELAPSED TIME',29X,'MONTHLY INFILTRATIO
     1N',/,5X,'LAYER NO.',4X,'YEARS   MONTHS',5X,'SURPLUS FOR LAYER',9X,
     2'IN INCHES')
      WRITE(6,236)
      GO TO 239
  237 INDIC=2
  238 FORMAT(//,6X,'PASSIVE',/,5X,'SOIL COVER',5X,'ELAPSED TIME',29X,'MO
     1NTHLY INFILTRATION',/,5X,'LAYER  NO.',4X,'YEARS   MONTHS',5X,'SURP
     2LUS FOR LAYER',9X,'IN INCHES')
      WRITE(6,238)
  239 ITIME=2
      GO TO 13
   20 STORPA(LAYPA)=STORPA(LAYPA)+ADDWAT
      IF(STORPA(LAYPA)-FCS)10,240,240
  240 ADDWAT=STORPA(LAYPA)-FCS
      STORPA(LAYPA)=FCS
      CALL TIMER(MONTH,LYEAR,JWATR,JJWAT)
      WRITE(6,232)LAYPA,LYEAR,MONTH,ADDWAT
      IF(LAYPA-IFEETS)242,241,242
  241 WRITE(6,236)
      INDIC=3
      GO TO 13
  242 LAYPA=LAYPA+1
      GO TO 20
   21 STORLF(LAYLF)=STORLF(LAYLF)+ADDWAT
      IF(STORLF(LAYLF)-FCL)10,243,243
  243 ADDWAT=STORLF(LAYLF)-FCL
      STORLF(LAYLF)=FCL
      CALL TIMER(MONTH,LYEAR,JWATR,JJWAT)
      WRITE(6,232)LAYLF,LYEAR,MONTH,ADDWAT
      IF(LAYLF-IFEETL)246,244,244
  244 INDIC=4
  245 FORMAT(//,20X,'ELAPSED TIME',10X,'LEACHATE AT',/,19X,'YEARS   MONT
     1HS',8X,'END OF MONTH')
      WRITE(6,245)
      GO TO 13
  246 LAYLF=LAYLF+1
      GO TO 21
   22 CALL TIMER(MONTH,LYEAR,JWATR,JJWAT)
  247 FORMAT(15X,I3,6X,I3,12X,F6.2)
      WRITE(6,247)LYEAR,MONTH,ADDWAT
      GO TO 10
  300 CONTINUE
  301 FORMAT(/,5X,'THANKYOU AND GOODBYE')
      WRITE(6,301)
      STOP
      END
```

5-10

```
      SUBROUTINE TIMER(MONTH,LYEAR,JWATR,JJWAT)
      LYEAR=0
      MONTH=JWATR-JJWAT
    1 IF(MONTH-12)3,3,2
    2 LYEAR=LYEAR+1
      MONTH=MONTH-12
      GO TO 1
    3 RETURN
      END
```

SAMPLE PROBLEM

```
 ACTIVE SOIL COVER CHARACTERISTICS
FIELD CAPACITY=  4.18  ORIGINAL MOISTURE CONTENT=  1.08  THICKNESS=  2 FEET
SOIL WILTING MOISTURE=  1.08

PASSIVE SOIL CHARACTERISTICS
FIELD CAPACITY=  4.18  ORIGINAL MOISTURE CONTENT=  1.08  THICKNESS=  0 FEET

LANDFILL CHARACTERISTICS
FIELD CAPACITY=  3.44  ORIGINAL MOISTURE CONTENT=  0.46  THICKNESS=  8 FEET


IN THIS PROBLEM NO.  1, LAYERS ARE TAKEN TO BE  1.00000 FEET THICK FOR COMPUTATIONS

THIS COMPUTATION ASSUMES THAT THE MATERIAL IS PLACED AT THE BEGINNING OF MONTH  1


  ACTIVE
SOIL COVER     ELAPSED TIME                                MONTHLY INFILTRATION
LAYER NO.    YEARS   MONTHS      SURPLUS FOR LAYER           IN INCHES
                                                                  3.40
    1           0        1              0.30
                                                                  2.95
    2           0        2              0.15


 LANDFILL      ELAPSED TIME                                MONTHLY INFILTRATION
LAYER NO.    YEARS   MONTHS      SURPLUS FOR LAYER           IN INCHES
                                                                  3.40
    1           0        3              0.57
                                                                  1.66
                                                                  0.18
                                                                 -1.09
                                                                 -1.32
                                                                  0.28
                                                                  0.21
                                                                  0.89
                                                                  2.78
    2           0       11              1.18
                                                                  3.03
    3           0       12              1.23
                                                                  3.40
    4           1        1              1.65
                                                                  2.95
    5           1        2              1.62
                                                                  3.40
    6           1        3              2.04
                                                                  1.66
    7           1        4              0.72
                                                                  0.18
                                                                 -1.09
                                                                 -1.32
                                                                  0.28
                                                                  0.21
                                                                  0.89
                                                                  2.78
                                                                  3.03
    8           1       12              2.70


               ELAPSED TIME           LEACHATE AT
              YEARS   MONTHS          END OF MONTH
            1       12               2.70
                                                                  3.40
```

```
5-12          2        1              3.40
                                                            2.95
              2        2              2.95
                                                            3.40
              2        3              3.40
                                                            1.66
              2        4              1.66
                                                            0.18
              2        5              0.18
                                                           -1.09
                                                           -1.32
                                                            0.28
                                                            0.21
                                                            0.89
                                                            2.78
              2       11              1.75
                                                            3.03
              2       12              3.03
                                                            3.40
              3        1              3.40
                                                            2.95
              3        2              2.95
                                                            3.40
              3        3              3.40
                                                            1.66
              3        4              1.66
                                                            0.18
              3        5              0.18
                                                           -1.09
                                                           -1.32
                                                            0.28
                                                            0.21
                                                            0.89
                                                            2.78
              3       11              1.75
                                                            3.03
              3       12              3.03
                                                            3.40
              4        1              3.40
                                                            2.95
              4        2              2.95
                                                            3.40
              4        3              3.40
                                                            1.66
              4        4              1.66
                                                            0.18
              4        5              0.18
                                                           -1.09
                                                           -1.32
                                                            0.28
                                                            0.21
                                                            0.89
                                                            2.78
              4       11              1.75
                                                            3.03
              4       12              3.03
                                                            3.40
              5        1              3.40
                                                            2.95
              5        2              2.95
                                                            3.40
              5        3              3.40
                                                            1.66
```

```
          5        4              1.66
                                                        0.18
          5        5              0.18
                                                       -1.09
                                                       -1.32
                                                        0.28
                                                        0.21
                                                        0.89
                                                        2.78
          5       11              1.75
                                                        3.03
          5       12              3.03

   END OF 72 MONTHS FOR PROBLEM  1

   THANKYOU AND GOODBYE
```